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# PREPARATION OF COAL-OIL MIXTURES FOR COMBUSTION BY CONTINUOUS GRINDING OF COAL IN OIL

Final Report

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## SUMMARY

The specific objectives of this study were to obtain performance data for grinding coal in oil with the existing small Szego mills, to design, build and test a larger prototype unit, to establish empirical scale-up parameters from the results, and to prepare a functional design of a commercial size mill for industrial or utility boiler use.

The novel Szego mill consists principally of a stationary, cylindrical grinding surface inside which a number of helically grooved rollers rotate, supported by flexible wire rope shafts. The design parameters of immediate interest were the diameter of the stator and the diameter and length of the rollers. Other design parameters are then matched to these in the light of the desired product specifications.

Some 250 experimental runs were carried out in the 22 cm diameter mill in several series using different coals, with water and with #2, #4 and #6 fuel oils. A larger, 45 cm diameter prototype mill was designed and built with two versions of rollers, and some 50 experimental runs were performed with it. This data base was sufficient, along with some earlier results and associated theoretical work to allow appropriate parameter identification and design conclusions.

A better optimized design for the prototype mill has been established and the new unit will be built. It will consist of eight rollers, 11 cm in diameter and 46 cm long, rotating in a 46 cm diameter cylindrical stator. It will be able to grind 2 to 2.5 tons of coal per hour

to the standard boiler size of 80% - 200 mesh (74 μm). Its estimated manfacturing cost is $40,000.00.

A functional design for the large commercial mill has been completed. It has a diameter of 130 cm and is equipped with 18 rollers, each 100 cm long and 17 cm in diameter. The mass of the rollers and the helical groove structure may be varied depending on product requirements. It should grind 15 to 20 tonnes per hour of coal to the standard boiler size, with an operating capacity range from 5 to 30 t/h. The estimated manufacturing cost is $150,000.

With a typical solids concentration of 40-50 weight per cent of coal in oil, these mills will be able to produce some 5 tonnes and 40 tonnes per hour of coal-oil mixture fuel, respectively. Comparison with conventional grinding equipment shows the Szego mill to have much higher capacity than other mills of comparable size. Power consumption for wet grinding is significantly lower than that of conventional equipment. While long-term operational experience with the mill is still inadequate, it is, nevertheless, expected that the Szego mill will be able to capture a meaningful market share of equipment used to prepare coal-oil or other coal slurry fuels.

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# INTRODUCTION

## The Szego Mill

The Szego mill consists of a stationary, cylindrical grinding surface inside which a number of helically grooved rollers rotate, being suspended by flexible wire rope shafts from flanges connected to a central drive shaft. The feed material enters at the top and the product is discharged at the bottom of the mill. The particles, upon entering the grinding unit are repeatedly crushed between the rollers and the stationary grinding surface. The crushing force is created mainly by the radial acceleration of the rollers. An important feature is the ability of the roller grooves to aid transport of the material through the mill, thus providing a means to control residence time and mill capacity. Schematic diagrams are given in Appendices I and III. The mill has been patented.

## Work Statement

With the broad objective of this project being that of obtaining sufficient performance and scale-up data to prepare a functional design of a commercial-size Szego mill, the main tasks were specified essentially as follows:

Two Canadian coals (New Brunswick Minto coal and Alberta Luscar coal) were to be used, with hard Pittsburgh coal used mainly for comparative purposes. The grinding was to be carried out in #4 and #6 fuel oils; this was later expanded to include #2 fuel oil and water. Tests were to be carried out in the existing, 22 cm diameter pilot size Szego mill using coal slurries of 15, 30 and 50 weight percent. Some coal containing 15% water

was also to be slurried in oil. The grind objective was to be nominal 80% - 200 mesh or finer. The resultant particle size distributions and power consumptions were to be measured for various operating conditions.

A large prototype Szego mill was to be designed, built and used to establish scale-up parameters. The contract was subsequently amended to use different internal combinations of rollers in the prototype mill. The final tasks were to establish a scale-up strategy, to do the actual, functional scaled-up design and to prepare a project report.

In this report the essential experimental results are summarized with illustrative data drawn from the various test programs. Some material which has already been analyzed and published is appended, and forms an integral part of the report, thus avoiding unnecessary repetition. Additional data are available.

## THE PASTE GRINDING PRINCIPLE

At the time that this project was initiated, an important discovery was made. In extending the coal-in-oil slurry grinding conditions to a more industrially suitable handling arrangement, it was found that mill performance could be greatly improved by going to a region of operation which in most other mills is less efficient, namely to the region of high solids concentrations. It turned out that mill capacity could be increased significantly and control over product size distribution somewhat improved by grinding the coal not in a freely-flowing liquid slurry, but by grinding it as a paste. This corresponded to about 60-65% by weight solids in water, and 60-75% solids in oil. Further work was, therefore, carried out under those conditions with the understanding that to prepare a lower concentration slurry for combustion purposes, it could be diluted either separately or by adding oil at the bottom of the mill below the grinding section. Patent applications for this process improvement have been filed.

It was found, further, and will be shown later that when grinding the coal as a paste, the results were substantially similar regardless of whether water or any fuel oil was used as a liquid. Both for this reason, and to improve the working environment in the building, a good portion of the experimentation was subsequently done with water in a paste mode rather than with the specified oils. This discovery also resulted in upgrading the proposed mill capacities by a factor of two from the original work statement.

All data reported herein have been obtained by grinding in the paste consistency range, i.e., typically 60-65 weight percent coal in water and 60-70% in oil.

## MAIN PARAMETERS OF STUDY

The main operating parameters of the mill were the rotational speed, the feed rate and coal/liquid ratio determining the coal-slurry or paste consistency. The main design variables were, for any mill diameter, the diameter and length of the rollers and the groove structure of the rollers, even though the latter was studied minimally for this project.

The material variables were the different kinds of coal: Pittsburgh, Minto and Luscar coals, and liquid: water and #2, #4 and #6 fuel oils. The feed coal was initially quite coarse, but later it was crushed to as least -½ and preferably -¼ inch size.

The dependent variables of the study were product particle size distribution, in particular the median size and the percentage passing 200 mesh (74 μm), and the energy consumption.

## RESULTS OBTAINED WITH 22 CM DIAMETER MILLS

Most of the experimental work was done in this existing mill with its original 30 cm long helically grooved rollers. Subsequently other rollers with triple-start helical grooves were used; one set was 30 cm in length and another 17 cm. All rollers were 9 cm in diameter and had coarse grooves. The three-roller configuration was always utilized. The parameters used in this mill were:

rotational speed: 900,1200, 1500 and 1800 rpm

feed-rate: 400, 800 and 1200 kg/h of coal

type of coal: Pittsburgh, Minto, and Luscar coals

liquids: water, #2, #4, and #6 fuel oils

A detailed analysis of early data obtained in that mill is presented in Appendix I, in the paper entitled "Grinding of Coal Slurries with the Szego Mill," presented at the symposium "Coal: Phoenix of the 80's" (Chemical Institute of Canada 64th Annual Meeting) in Halifax, June 1981. This paper gives a description of the mill, including a schematic layout, reviews the previous experimental work which was utilized as part of the scale-up effort, deals with the experimental conditions used at that time and gives an extensive set of data which must be considered an integral part of this scale-up project report. The "Summary and Conclusions", giving the significant performance results for the 22 cm diameter mill are reproduced here.

"Summary and Conclusions

Experiments were carried out in a 22 cm diameter mill equipped with three 30-cm long rollers, coarse-grooved in a single-start helical pattern. The rotational speed range was 1200-1800 RPM. Coal feed rates varied from 400-1200 kg/h, giving total coal and liquid feed rates from 600-2000 kg/h. Summarizing:

- In a single pass, typically 50-90% of the coal is crushed to -200 mesh (- 74 μm).
- In multipass operation, a 12-20 μm median size is readily obtained in 2-3 passes through the mill.

- The benefit of grinding beyond a 2nd or 3rd pass is minimal; a limiting size of 10-12 μm is apparent with the rollers used.
- High rotational speed and low feed rate enhance the rate of grinding.
- The differences between the grinding results with different coals and in different media were minor compared to large difference in physical characteristics of the coals and viscosities of the liquids.
- Typically the specific energy consumption for bringing the coal to 80% passing 200 mesh in #2 oil is 25-40 kWh per ton of coal, with slightly lower values in water and higher values in #4 oil (or hot #6 oil).
- For a 15 μm median size product, the corresponding values are 50-80 kWh/ton of coal.
- At optimized operating conditions the specific energy consumption should not exceed the lowest values reported above."

In the following sections, some data from Appendix I are extracted for comparative discussion and other results not included in that paper, or obtained subsequently, are used to selectively illustrate the various aspects and results of the test program with the pilot-size mill.

## Typical Results

Figure 1 gives a typical set of data plotted as weight percent passing any stated size, obtained with Minto coal in #2 fuel oil fed to the 22 cm mill at a rate of 800 kg/h as a 65% coal paste. The mill was operated at 1200 rpm and data for 1, 2 and 3 passes through the mill are presented.

It is observed that in the first pass, a median particle size of 40 microns is attained, and about 65% of the coal is smaller than 74 microns. After the third pass the median size is reduced to 22 microns and 92% of the material passes through a 200 mesh screen. The product size distributions depicted are typical for standard or average operating conditions. It is possible to change these to give either narrower or broader size distributions as may be desired over at least a modest range of slope variations.

## Effect of Rotational Speed

Figures 2 and 3 provide data for the variation of the median particle size and the percent finer than 74 microns with rotational speed. Two series of tests are combined in these figures. The first were obtained using single lead rollers and cover the range 1200 to 1800 rpm. Later, more data were obtained using triple lead rollers, at 900 and 1200 rpm. A constant feed rate of 800 kg/h of Pittsburgh coal has been chosen, ground as paste in #2 oil. The values plotted in Figures 2 and 3 are taken from complete size distributions such as shown in Figure 1, at the 50% undersize value from the abscissa, and from the 74 micron value on the ordinate.

The difference between the two sets of data (shown at the 1200 rpm value) is not only due to roller design but may include other effects such as sample coal grindability variations or somewhat different paste consistencies. The differences are largest after the first pass but have virtually vanished after three passes through the mill.

These data indicate that the desirable operating speed for this mill is about 1200 rpm. At lower speeds, as shown by the 900 rpm results, grinding performance drops off quite rapidly. Operating at speeds above 1200 rpm exposes the mill to considerably greater mechanical strain and increased wear, while only a relatively modest gain in fineness is obtained, particularly so in the second and third passes. Power consumption is also much higher. If a finer particle size is desired, a different roller configuration should be utilized.

Effect of Feed Rate

Figures 4 and 5 provide similar data on the variation of median particle size and percent passing 74 μm with feed rate. This time a rotational speed of 1200 rpm has been chosen and Alberta Luscar coal, ground with single lead rollers in #2 oil for 1, 2 and 3 passes is shown. It is apparent in both figures that the higher the feed rate the coarser the material, and that the variation over the range shown is more or less linear.

It is also observed in Figure 4 that the median particle size changes greatly from the first to the second pass and that there is only a relatively small change from the second to the third pass. At 800 kg/h the medians size goes from 55 microns after the first pass to 28 microns after

the second, and then from 28 to 25 microns only after the third pass. This is indicative of approaching a limiting particle size for this speed and these rollers. On the other hand, one observes in Figure 5 that the percentage passing 200 mesh continues to increase significantly from the first to the second and from the second to the third pass. The corresponding changes at 800 kg/h are from 59 to 78% and from 78 to 86%, respectively. These figures indicate that while the finer size is not ground much finer with additional passes and the median size does not change very much, the coarser end continues to be ground finer and the particle size distribution becomes steeper.

It should be noted that at the higher feed rate of 1200 kg/h of coal, the total feed to the mill is essentially 2 tons of material per hour through its 22 cm diameter. This is a respectably high capacity and the product, after three passes, is essentially in the standard boiler fuel range. It is observed that about the same percentage (75 to 80%) passing 200 mesh is found with three passes at 1200 kg/h, or two passes at 800 kg/h and one pass at 400 kg/h.

Different Coals and Liquids

Figure 6 presents the data for both the Minto and the Luscar coals obtained at the high rate of 1200 kg/h of coal, at a rotational speed of 1800 rpm in #2 fuel oil. It is observed that there is a noticeable difference in the grind of the two coals after the first pass, of about 10 μm in median size, which falls to less than 1 μm after the third pass. This is a relatively small difference and the second and third pass results are essentially equal if reproducibility of the data is considered.

The same question is addressed in Figure 7 with all comparable data utilized. The percentage of Luscar coal retained on a 200 mesh screen after grinding is plotted versus the comparable value for Minto coal, i.e., for the same feed rate, rotational speed, oil and number of passes. It is obvious that the bulk of the data points lie above the diagonal line. For very fine grinding, i.e., a low percentage retained, the difference becomes quite small compared to data scatter. Agreement with the selected conditions shown over the full size range in Figure 6 is apparent.

Figure 8 gives similar data for the Pittsburgh versus the Minto coal. The data points are spread fairly evenly around the diagonal, indicating the same grinding performance for both coals. The reported Hardgrove grindability indices (HGI) are 45, 65 and 65 for the Luscar, Minto and Pittsburgh coals, respectively. As the HGI is defined for much coarser grinding, direct comparison is difficult. Results are obviously in qualitatively agreement with expectations from the HGI values. The effect of grindability variations is, however, believed to be smaller than with conventional equipment. This statement is based, in part, on other results obtained with very diverse materials.

To show the effect of the liquid used, Figure 9 provides data obtained at 900 rpm with Pittsburgh coal at a feed rate of 800 kg/h ground in water and in #2 oil. It is apparent that when the appropriate paste thickness of the material is used, the data virtually overlap. The discrepancies shown are comparable to the experimental errors arising both from the grinding experiments and from sample analysis.

An additional illustration of this similarity of mill performance with different liquids is given later using data obtained with water and #4 fuel oil.

It is observed in Figure 9, again, that from the first to the third pass, the size distribution gets to be somewhat steeper, with more grinding taking place selectively at the coarse end.

Effect of Roller Length

In order to study the effect of roller length with the same roller diameter, a set of short rollers was built and used in the 22 cm diameter mill. Compared to the standard length of 30 cm, these rollers were 17.5 cm in length, while in all other respects they were identical to the longer rollers. An indicative set of data allowing easy assessment of the effect of length is given in Figure 10. In this figure the ordinate represents the percentage of the product above the stated sizes of 45, 75, and 150 μm obtained from size distribution plots for several passes through the mill. The abscissa gives the cumulative length of the rollers, one pass through the mill corresponding to 30 cm for the longer rollers and 17.5 cm for the shorter ones. The data extend over 5 passes with the 17.5 cm rollers and 3 passes with the 30 cm rollers and were obtained at 1200 rpm with 800 kg/h of Pittsburgh coal ground as a paste in water.

It is apparent that the incremental lengths from each of the two roller combinations are additive and that any end effects are insignificant. It can be concluded, therefore, that over this range of roller length to diameter ratios, there is no noticeable effect of roller length. It would have been interesting to extend this study to longer rollers but for

practical reasons of time and cost this was not possible. Such experiments will be carried out at a future date.

Moisture in Coal

In addition to studying the grinding of essentially dry coal in oil, it was, according to the work statement, also necessary to study the grinding of wet coal in oil, with the coal containing 15% moisture. These experiments were carried out and it was observed that so far as grinding performance was concerned, the effect of the added water was insignificant. The water, to the extent that it was initially adsorbed in the pores of the coal particles , stayed with the coal particles and did not separate out as droplets. If, on the other hand, the water was added to the mill with the coal and oil, rather than adsorbed onto the coal earlier, tiny water droplets were found in the oil phase and upon shearing, these droplets would coalesce and form bigger drops.

## RESULTS OBTAINED WITH 45 CM DIAMETER MILL

### Mill Configurations

This larger prototype mill with twice the diameter of the pilot size mill was built with two different roller configurations. In the first configuration, eight 9-cm diameter rollers of the same design as used in the small mill were placed around the periphery of the larger diameter mill, with the central shaft made correspondingly larger in order to reduce bypassage of unground material. The data so obtained could then be compared directly with results from the smaller mill, at the corresponding relative rotational speeds.

In the second configuration the rollers were built 40 cm long which was the maximum length that could be accommodated in the mill body. In order to bridge the range of plausible roller diameters, this combination was a geometric scale-up with double the roller diameter, (i.e., about 18 cm). Those rollers were also much heavier than the smaller ones, since the wall thicknesses were considerably larger and the internal structure weighed much more per unit length and unit diameter.

This 45 cm diameter mill was somewhat too large for our laboratory facilities. As its power requirements exceeded available supply, it could not be run over its full range of designed speeds and loadings. Operating conditions had to be limited to the lower range of rotational speeds of 400 and 600 rpm. The feed rates used were approximately 1200, 2100, and 3100 kg of coal per hour, for both the roller combinations. Minto and Pittsburgh coals were ground in water and in #2 and #4 fuel oils.

Results with Small Rollers

Illustrative data, obtained with 3100 kg/h of Minto coal in water and the mill operating at 600 rpm, are shown in Figure 11 for 1, 2, 3 and 4 passes. Also shown on the same graph are data taken from the small mill at 1200 and 900 rpm, obtained with Pittsburgh coal fed at a rate of 1250 kg/h. Only first pass results from the small mill are shown, over the sieve analysis size range.

It should be realized that with the same rollers, but twice the diameter of the mill, the 600 rpm speed in the larger mill corresponds to 1200 rpm in the smaller mill in order to attain the equivalent peripheral velocity of the rollers. Since the centrifugal force varies with rpm squared times radius, the centrifugal forces in the larger mill at 600 rpm are equal to those obtained in the smaller mill at 900 rpm. Furthermore, with eight rollers in the larger prototype mill and three rollers in the smaller mill, the amount of coal per roller is about 400 kg in either mill at their given feed rates. One would therefore expect quite similar products from either mill at equivalent centrifugal forces or peripheral velocities.

It is observed that the first pass data from the larger mill at 600 rpm and the 1200 rpm data from the smaller mill are in relatively good agreement. What this suggests is that the peripheral speed as a correlating parameter is more important than force. The lower force at the 600 rpm rotational speed in the bigger mill is apparently adequate to crush the coal particles just as well as the higher force exerted in the smaller mill at

1200 rpm. It will be seen later that using excessive forces for crushing coal is wasteful insofar as energy consumption is concerned.

Comparing the power consumption at these conditions, one would find that for 80% passing 200 mesh, i.e., the standard boiler feed size, which is obtained just beyond the third pass in the larger mill, requires a specific energy consumption of 21 kWh/t drawn from the power lines. The comparable small mill value at the stated conditions was almost 30 kWh/t and the energy consumption with the heavier rollers was almost 40 kWh/t. These numbers are in approximate proportion to the centrifugal forces exerted under the various grinding conditions, for the same product size criterion.

Results with Large Rollers

As already pointed out, the large rollers were much heavier, both on a per unit length and diameter basis, compared to the small rollers. The crushing forces were, therefore, very large indeed and the power drawn was correspondingly high. For coal, a material which is crushed relatively readily, such a force is excessive and a dedicated mill design must take this into account. For other materials where greater crushing forces are required, the heavier rollers may gain more in grinding performance than the loss in energy and may, therefore, be appropriate. This likelihood indicates the need to tailor-make mill internals for individual applications.

Some representative data are shown in Figure 12 for Pittsburgh coal fed at a rate of 2150 kg/hr in #2 oil, for 1, 2, 3, 4 and 5 passes. The usual trends are again observed with the coarsest product in the first pass having a median size of 63 microns and 55% being finer than 200 mesh.

In this 600 rpm operation the percentage passing 200 mesh increases to 86% for the 5th pass.

The product size distributions are a little broader than in some of the earlier illustrations. This is probably because of the relatively large distance between rollers which allows some of the coarser component to by-pass the rollers and also because of the larger crushing forces, the fine end is ground somewhat finer. It is interesting to note that the particular size distribution obtained with these large rollers happen to be very close to the "ideal" size distribution required to obtain the minimum viscosity for coal-oil slurries.

Additional data on grinding performance are given in Figures 13 and 14. Figure 13 shows the data obtained with Pittsburgh coal in water, and in #2 and #4 oils at a constant feed rate of 2100 kg/h of coal and at a rotational speed of 600 rpm. These data indicate that the grinding performance of this mill on coal slurries (when ground in the paste mode) is virtually unaffected by the slurry mediums examined. If anything, grinding in the viscous #4 oil is better than in water. Similar results would be obtained if median sizes were examined rather than the percentage passing 200 mesh shown in Figure 13.

In Figure 14 the grinding performance at various feed rates for Pittsburgh coal in water is shown as a function of the number of passes. It is observed that there is only a minimal difference with feed rate. In the first pass 61% of the coal is finer than 200 mesh, compared to the barely lower 57% and 55% when the feed rate is increased by 1.8 and 2.6-fold, respectively. This again demonstrates that the forces developed in this

mill are so large that the rollers should be able to grind at a much higher feed rate, before a serious reduction in performance would occur. Note the contrast with the data given in Figure 5, where significant variations with feed rate were observed.

Whereas in the smaller mill it was observed that the power consumption increased with the viscosity of the liquid medium, particularly when #4 oil was used (see for example Figure 10 of Appendix I), with the very much greater forces exerted by the big, heavy rollers, this difference becomes minor. The cumulative specific energy consumption with #4 oil (49 kWh/t after three passes) is only slightly larger than with water (41 kWh/t). It is conceivable that, if it had been possible to push the larger mill to higher feed rates, the specific energy consumption for the same grinding would have been reduced accordingly, to come into closer agreement with the earlier results.

Comparison of Results

Comparison of these results with the ones presented in Figure 11 for the eight smaller rollers leaves the general impression that the grinding performance results are comparable, but the heavy, large rollers draw significantly more power,almost by a factor of two. It must also be realized that these larger rollers are somewhat longer, 38 cm versus 30 cm. Thus, it must be concluded that the eight smaller, lighter rollers perform better as they provide better grinding per unit length and draw less power.

## SCALE-UP STRATEGY

### Grinding Mechanism

It is necessary here to focus attention, at least briefly, on the question of how the coal is ground. It would appear that there are at least two mechanisms involved. The first is crushing of the coal particles as they are caught between the roller and the stationary grinding surface (stator), either by direct contact with these surfaces or by having the crushing pressure exerted from particle to particle. The second is breaking the particles by material shearing action in the mill. As the rolls move at high speed past the stator surface, the material is caught under the rollers and forced to move at high relative velocities between the roller and the stator. Very high velocity gradients result. The shearing forces will obviously depend on both the velocity gredient and the slurry or paste viscosity. Therefore, one would expect a greater contribution from the shearing action when the viscosity is very high, i.e., when grinding occurs in the paste. These phenomena are currently being studied but no definitive conclusions can be drawn at this stage about their relative importance.

### Importance of Groove Structure

In another project a theoretical, predictive model has been set up to study the dynamics of the roller motion past the stator surface, and the fluid flow pattern arising as the paste is displaced from the front of the roller, either through the narrow gap between the roller and the stator or into the roller grooves. From this model it is possible to establish certain limits on the approach distance of the rollers to the grinding

surface which, in turn, can be related to the dimensions over which crushing action may be predominant. Some confirmation to this theoretical work has been obtained from various data, including the data presented here.

Both this work and other experimentation have shown that the groove design is important and one can change or optimize the particle size distribution for specific purposes by choosing the appropriate groove design. Further work is contemplated in this area so that one can choose optimal groove design for any particular mill body diameter and roller mass and diameter in combination with the desired product size distribution.

Scale-up Parameters

Both from the empirical, conceptual approach and from this dynamic modelling approach, it is concluded that the peripheral velocity as well as the crushing force per unit length and roller diameter are important parameters. The peripheral velocity can be changed by the speed of rotation, it being proportional to rpm and mill diameter, and independent of roller diameter. The crushing force depends not only on rpm squared and mill diameter, but also on roller mass, i.e., its diameter and its internal design.

Both the peripheral velocity and the crushing force enter in establishing the approach distance of the rollers to the grinding surface. The groove structure and slurry or paste physical properties also enter in these complicated relationships.

In addition to their aforementioned importance, the roller groves have yet another important function, namely that of helping to transport the

material through the mill. It is, therefore, always important to assure adequate transport capability for the desired mill throughputs when selecting the groove structure.

Any further discussion of these design aspects goes beyond the purposes of this report. May it suffice to state that a combined application of the aforementioned approaches, parameters and criteria will suggest plausible roller sizes for the 45 cm prototype mill. It will also allow the establishment of the functional design, i.e., the essential dimensions of the full-scale industrial mill. Some uncertainties in the scale-up remain, in part because the effect of roller length has not been studied over a sufficiently wide length-to-diameter range, but these are not serious.

## MILL DESIGNS

### Optimized Prototype Mill

Based on the preceeding data, a more optimized roller and body configuration for the large prototype mill would be to use eight, 11 cm diameter rollers in a 46 cm diameter mill with a grinding surface length of about 46 cm.

Such a mill is currently being designed and should be built and tested with various roller groove configurations. The mill is expected to have the capacity to grind 2000-2500 kg/h of coal to 80% minus 200 mesh, with an operating capacity range for various product sizes of around 1 to 4 tonnes of coal per hour.

### Large Industrial Mill

Following similar considerations and wishing to use the rollers of the diameter and approximate weight as have already been tested, i.e., the 17.5 centimeter rollers, the functional design parameters have been selected as follows:

inside diameter - 130 cm

roller diameter - 17.5 cm

length of rollers - 100 cm

number of rollers - 18

The groove structure on the rollers must be such that it is able to transport coal at a sufficiently rapid rate and may be adjusted along with the mass of the rollers to obtain desired specific grinding objectives.

This mill is expected to have an operating capacity range from 5 to about 30 tonnes of coal per hour and the ability to grind 15 to 20 t/h to a standard boiler size of 80% passing 200 mesh.

While this is a significant scale-up from the tested sizes, it should be pointed out that the same diameter rollers have already been tested in the prototype mill and any uncertainty is thereby greatly reduced. The dynamic, predictive model can be used to confirm the expectations, and the large diameter mill with 18 rollers and a correspondingly larger diameter shaft is not in principle or dynamically very different from the smaller versions already tested. The scale-up expectations can therefore be relatively certain, and could well be improved upon by judicious selection of groove structures.

## COMPARISON WITH OTHER MILLS

### Mill Performance

There is a minimum of comparative mill performance information publicly available for wet grinding of coal in oil. Appendix II consists of a paper entitled "Preparation of Coal-Oil Mixture Fuels," presented at the 2nd World Congress of Chemical Engineering in Montreal, October 1981. In addition to outlining a possible strategy of coal-slurry fuels preparation and utilization, it provides a brief comparison of the Szego mill with other equipment for wet grinding of coal. The particular data used are available in the literature and are based on a one ton per hour coal-oil mixture (COM) preparation capability. Appendix II also serves to present the case of on-line coal slurry fuels preperation, in a sense the "raison d'être" for this scale-up study.

A ball mill capable of producing 1 t/h of COM, ground to a 75% minus 200 mesh product at 55% concentration from a starting feed size of 3 mm, is 2.4 m long and 1.2 m in diameter, containing 3.7 tons of balls, and draws 29 kW of power. It rapidly loses grinding efficiency as the concentration level is raised to 60%.

The Attritor is an efficient agitated media mill in the relatively fine grinding range. However, these mills are typically larger than ball mills for similar service, and have a higher power consumption for the same grinding performance. A specific energy consumption of 70 kWh/t of coal, or half that figure on COM tonnage basis, is reported. The Tower mill is reported to have lower power consumption than other agitated media mills, but its grinding rate is also lower requiring an even larger mill volume.

The 22 cm diameter pilot Szego mill is able to produce 1 ton of COM of the same specifications with a power consumption of 25 to 40 kWh/t of coal depending on oil viscosity, or around 15 kWh/t COM. For the same task it is obviously an order magnitude smaller than the other mills and its power consumption is also significantly lower than that reported for other wet-grinding mills. Table I summarizes these comparative features. In an independent study of coal-oil mixture preparation technologies, Singh in an Ontario Hydro Research Division Report (No. 81-91-K 1981) concludes that "a preparation system based on the Szego mill is the most attractive because of economy, low complexity and safety of operation."

Table I Comparison of wet grinding mills for the preparation of 1 t/h coal-oil mixture.

| | Agitated Media Mill | Ball Mill | Szego Mill |
|---|---|---|---|
| Approximate dimensions | | | |
| diameter, m | 1.2 | 1.2 | 0.3 |
| length, m | 2.5 | 2.4 | 0.5 |
| Power consumption, kW | 35-50 | 20-30 | 12-20 |

Operating Experience

The Ball mill has a long history of operation, and while data on the performance of large ball mills in COM service appear not to have been published, there is no doubt about the general reliability of such mills.

Mechanical complexity is minimal, and as balls wear down, their replacement is easy.

Significant operating experience has also been accumulated about agitated media mills, particularly in small sizes. Mechanical complexity is somewhat greater than that of the ball mill, and the agitating drive assembly is also susceptible to considerable wear.

The Szego mill does not yet have an industrial use track record, although a number of test installations have been made, and have operated for many hundreds of hours. Its internal mechanical complexity is greater, and it is, particularly in small sizes, more susceptible to wear than the mills just mentioned. However, its total operating systems for preparing COM fuels is simpler than that of the other mills.

The limited wear information available suggests that for coal-in-oil or coke-in-oil service with rollers of hardened steel, the small, 22 cm diameter mill may have a useful lifetime of 1500-2000 hours, with at least twice that time expected from the larger unit. In corrosive service, wear rates are higher and a higher nickel or chromium steel is required. For more abrasive service, consideration has been given to casting the rollers of manganese steel or other very hard materials.

In early installations there have been problems with roller bearings. These have been traced in part to operating conditions; a feed of preferably -¼ inch size supplied to the mill at a steady rate is essential and greatly reduces mechanical strains to which the equipment is otherwise exposed. Some design improvements have also been made to enhance reliabilty, with apparent success judging from more recent installations.

Changing the roller assembly in the small mill is quite easy and can be accomplished in half an hour so that any maintenance downtime can be kept very short.

While it is too early to make very definitive statements, it would appear that the advantages of the Szego mill, its good performance, high capacity and resultant modest cost per unit of capacity, more than make up for the remaining uncertainties and possibly higher maintenance costs. Lately, industrial interest in the Szego mill has increased considerably.

It is imperative to build both sizes of mills described here. The 46cm diameter mill, with the optimized internals for desired production rates, may satisfy small industrial boilers. The larger units, capable of producing up to 40 tonnes per hour of coal-oil mixture fuel in an on-line operation would be suitable candidates for large industrial or utility boiler installations or for the production of coal-oil mixtures for central production facilities.

A 3 stage mill using four standard, 9 cm diameter rollers in a 27 cm diameter body has been designed and built. Its grinding capability with the twelve rollers is about four times that of the small, 22 cm diameter mill. It is intended for use in applications where fine or ultra-fine grinding is required, necessitating multipass operation. The 3 stage unit reduces intermediate handling and allows use of different roller configurations in the different stages. Rollers with finer grooves may, for example, be used in the later stages.

General Comminution, Inc. has just produced the first version of a Szego mill brochure, in anticipation of further serious industrial interest. A copy is enclosed as Appendix III.

# FIGURES

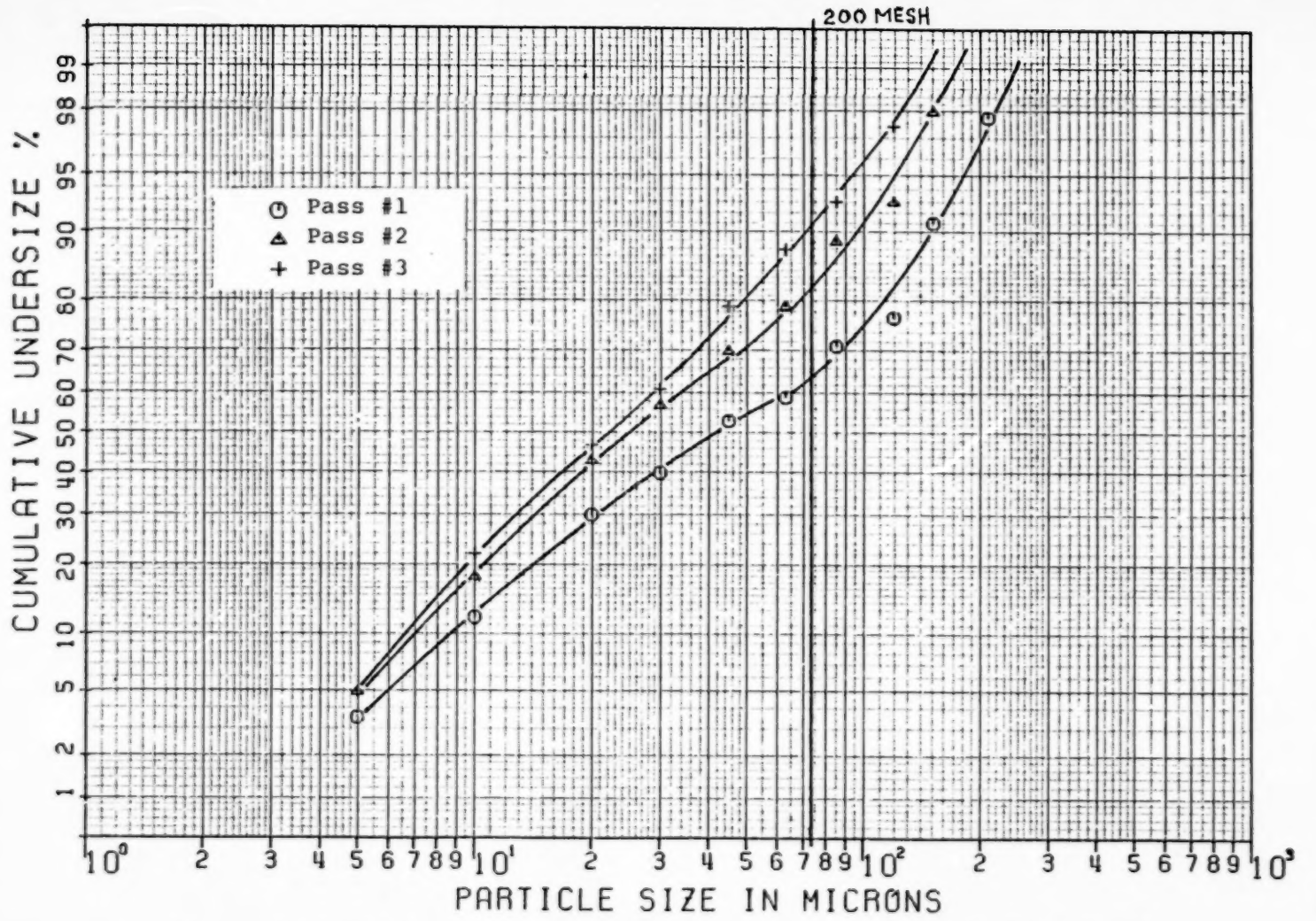


Figure 1 Particle size distributions for grinding Minto Coal in #2 oil; single lead rollers; 1200 rpm, 800 kg/h of coal.

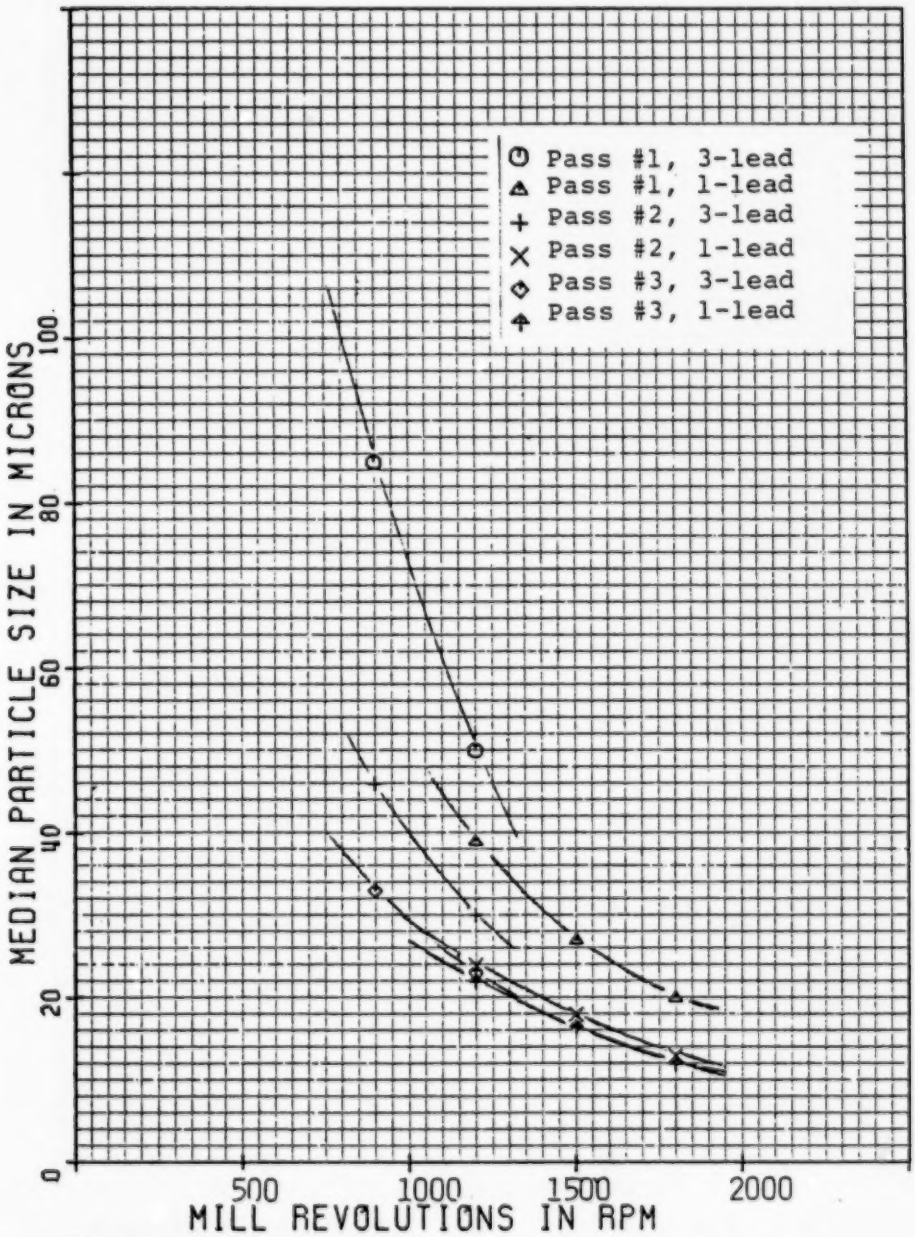


Figure 2 Median particle size as a function of rotational speed; Pittsburgh coal in #2 oil, 800 kg/h; single and triple lead rollers

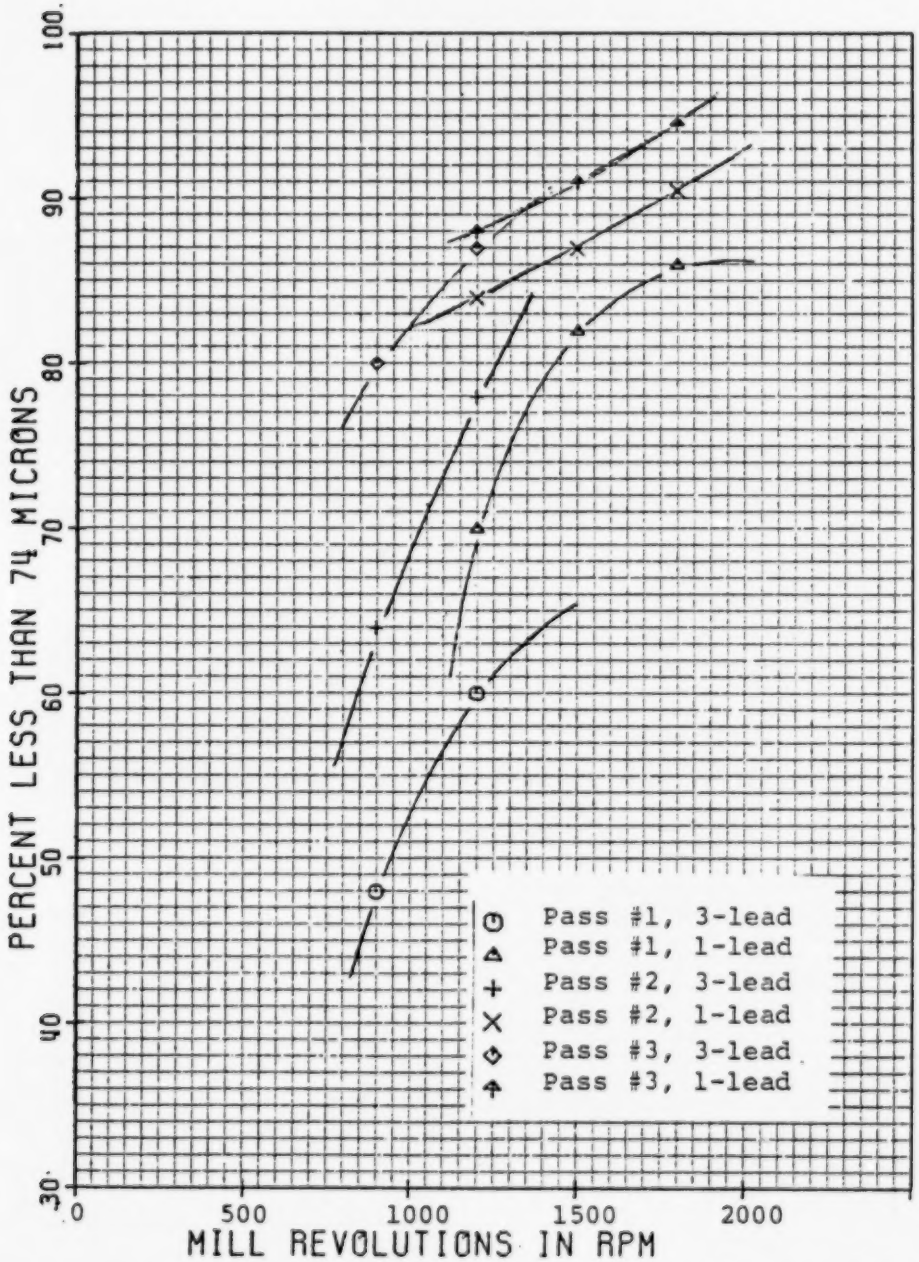


Figure 3 Percentage of coal less than 74 μm as a function of rotational speed; Pittsburgh coal in #2 oil, 800 kg/h; single and triple lead rollers.

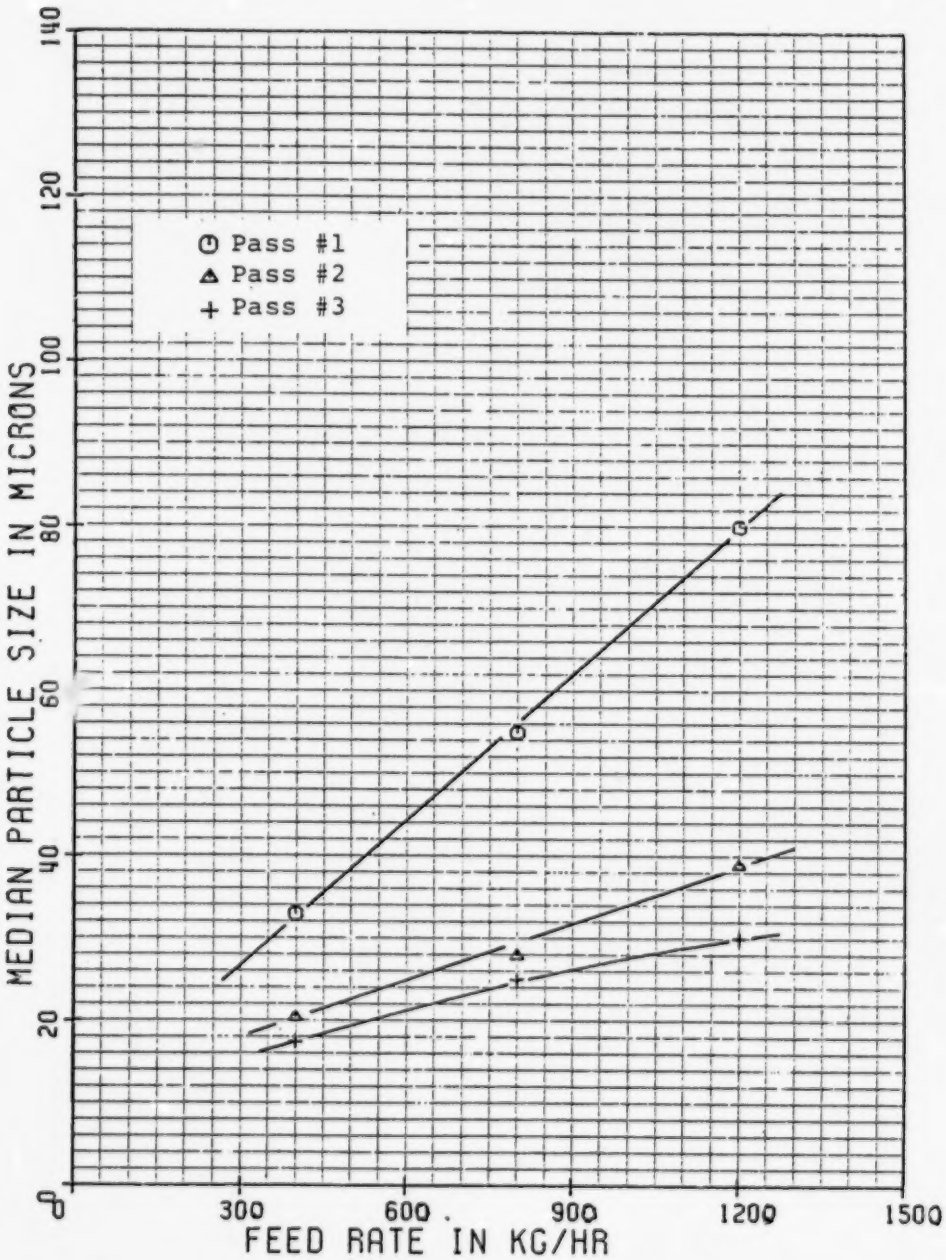


Figure 4 Median particle size as a function of feed rate; Luscar coal in #2 oil, 1200 rpm, single lead rollers.

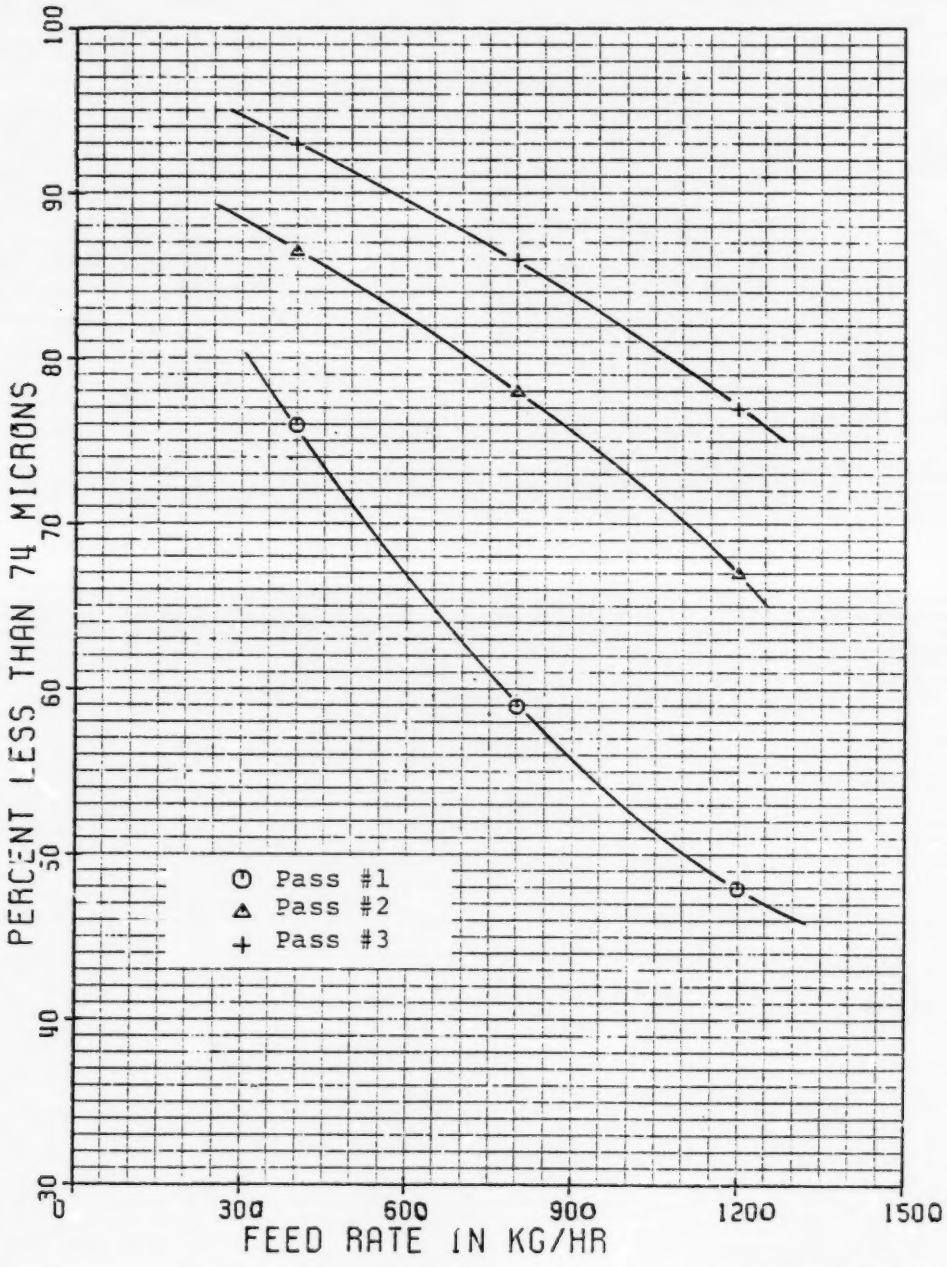


Figure 5 Percentage of coal less than 74 μm as a function of feed rate; Luscar coal in #2 oil, 1200 rpm, single lead rollers.

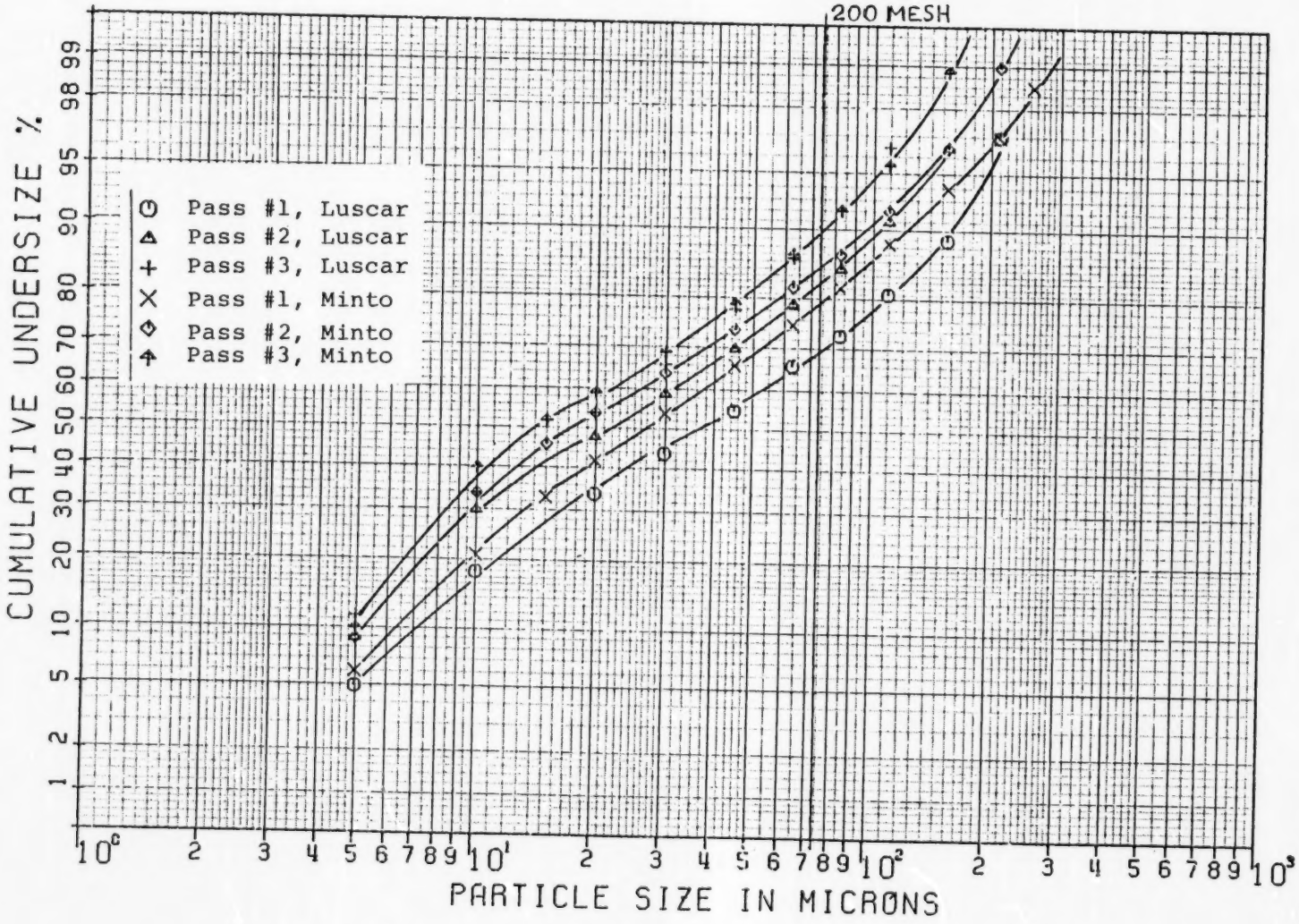
200 MESH
CUMULATIVE UNDERSIZE %
1 2 5 10 20 30 40 50 60 70 80 90 95 98 99
Pass #1, Luscar
Pass #2, Luscar
Pass #3, Luscar
Pass #1, Minto
Pass #2, Minto
Pass #3, Minto
10⁰ 2 3 4 5 6 7 8 9 10¹ 2 3 4 5 6 7 8 9 10² 2 3 4 5 6 7 8 9 10³
PARTICLE SIZE IN MICRONS

Figure 6 Particle size distributions for grinding Luscar and Minto coals in #2 oil; single lead rollers, 1200 kg/h of coal, 1800 rpm.

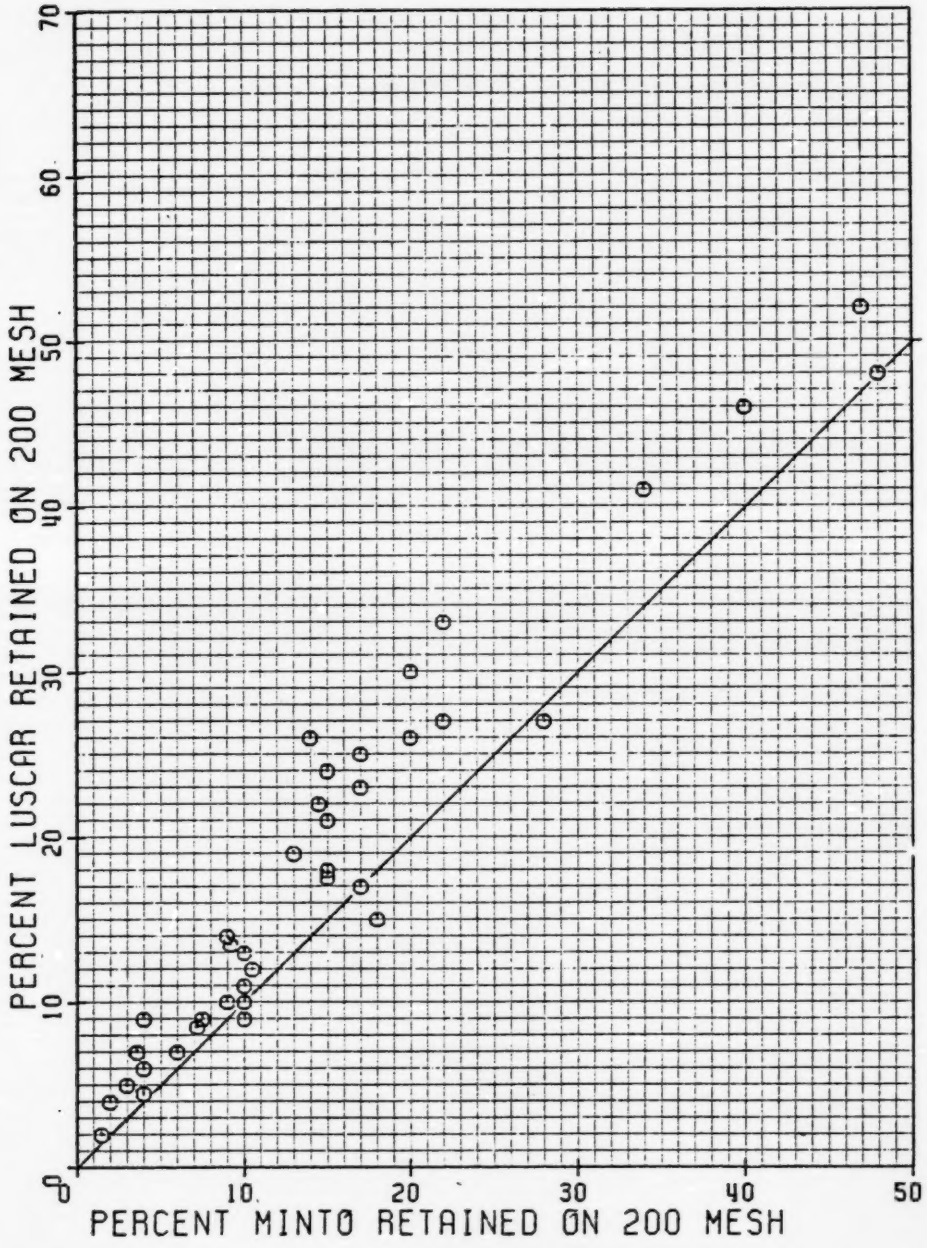


Figure 7 Comparative grinding performance of Luscar and Minto coals in oil.

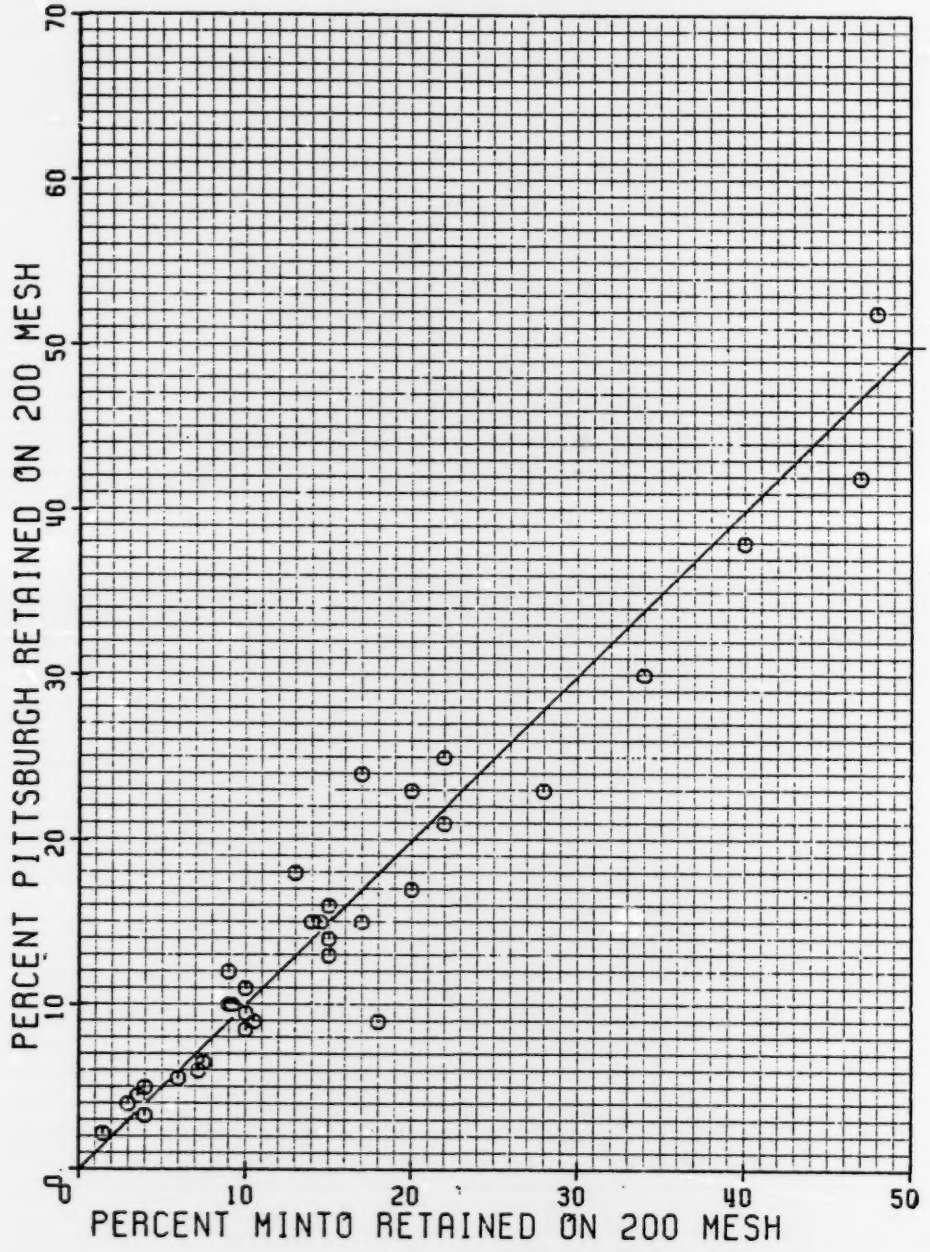


Figure 8 Comparative grinding performance of Pittsburgh and Minto coals in oil.

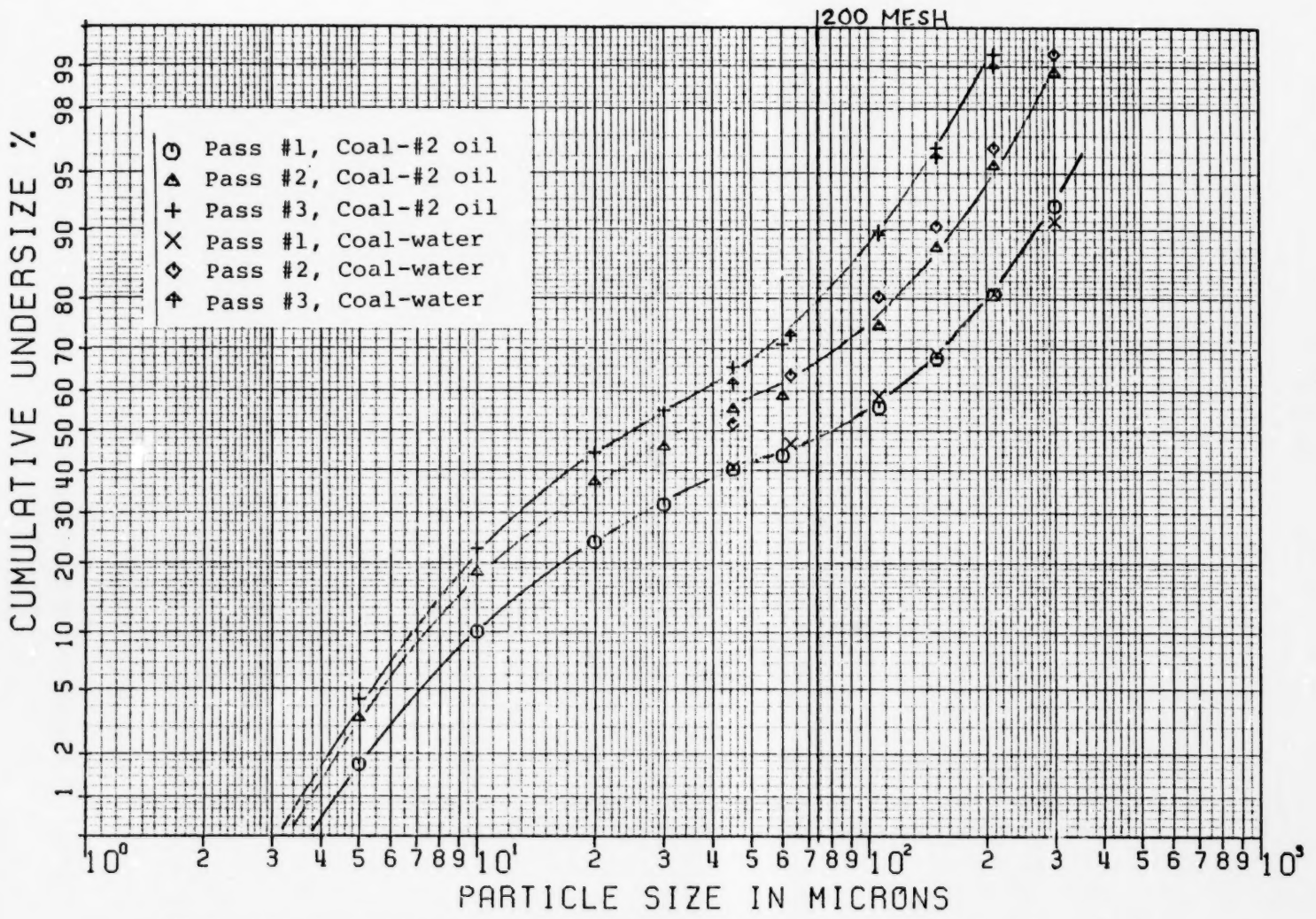
200 MESH
Pass #1, Coal-#2 oil
Pass #2, Coal-#2 oil
Pass #3, Coal-#2 oil
Pass #1, Coal-water
Pass #2, Coal-water
Pass #3, Coal-water
CUMULATIVE UNDERSIZE %
1 2 5 10 20 30 40 50 60 70 80 90 95 98 99
10⁰ 2 3 4 5 6 7 8 9 10¹ 2 3 4 5 6 7 8 9 10² 2 3 4 5 6 7 8 9 10³
PARTICLE SIZE IN MICRONS

Figure 9 Particle size distribution for grinding Pittsburgh coal in #2 oil and water; 800 kg/h of coal, 900 rpm, triple-lead rollers.

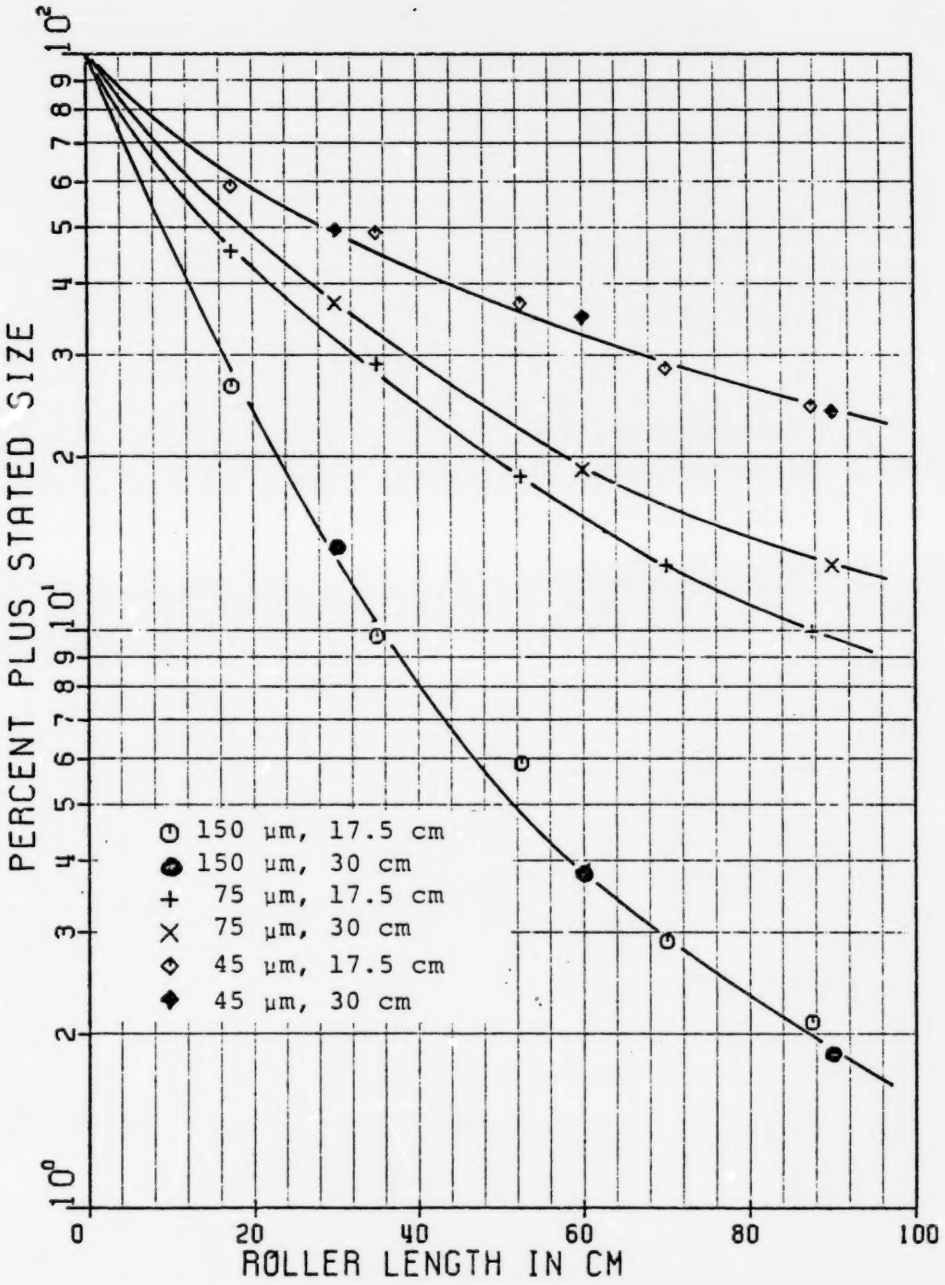


Figure 10 Percentage of coal greater than stated size, as a function of cumulative roller length; 1200 rpm, 800 kg/h of Pittsburgh coal in water; triple-lead rollers.

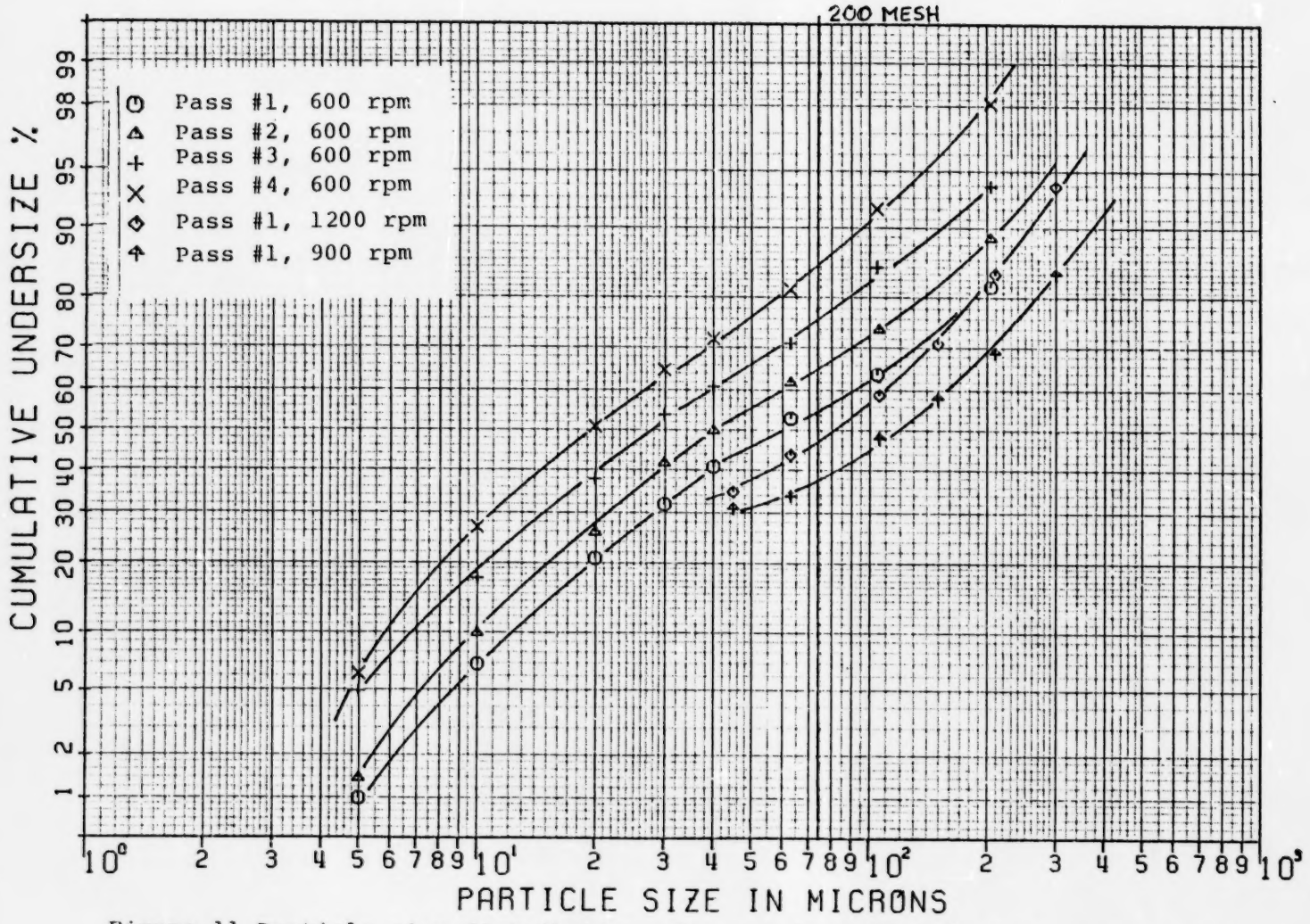


Figure 11 Particle size distributions for grinding Minto coal in water, eight roller mill, 3100 kg/h, 600 rpm, 4 passes; Pittsburgh coal in water, three roller mill, 1250 kg/h, 900 and 1200 rpm, one pass.

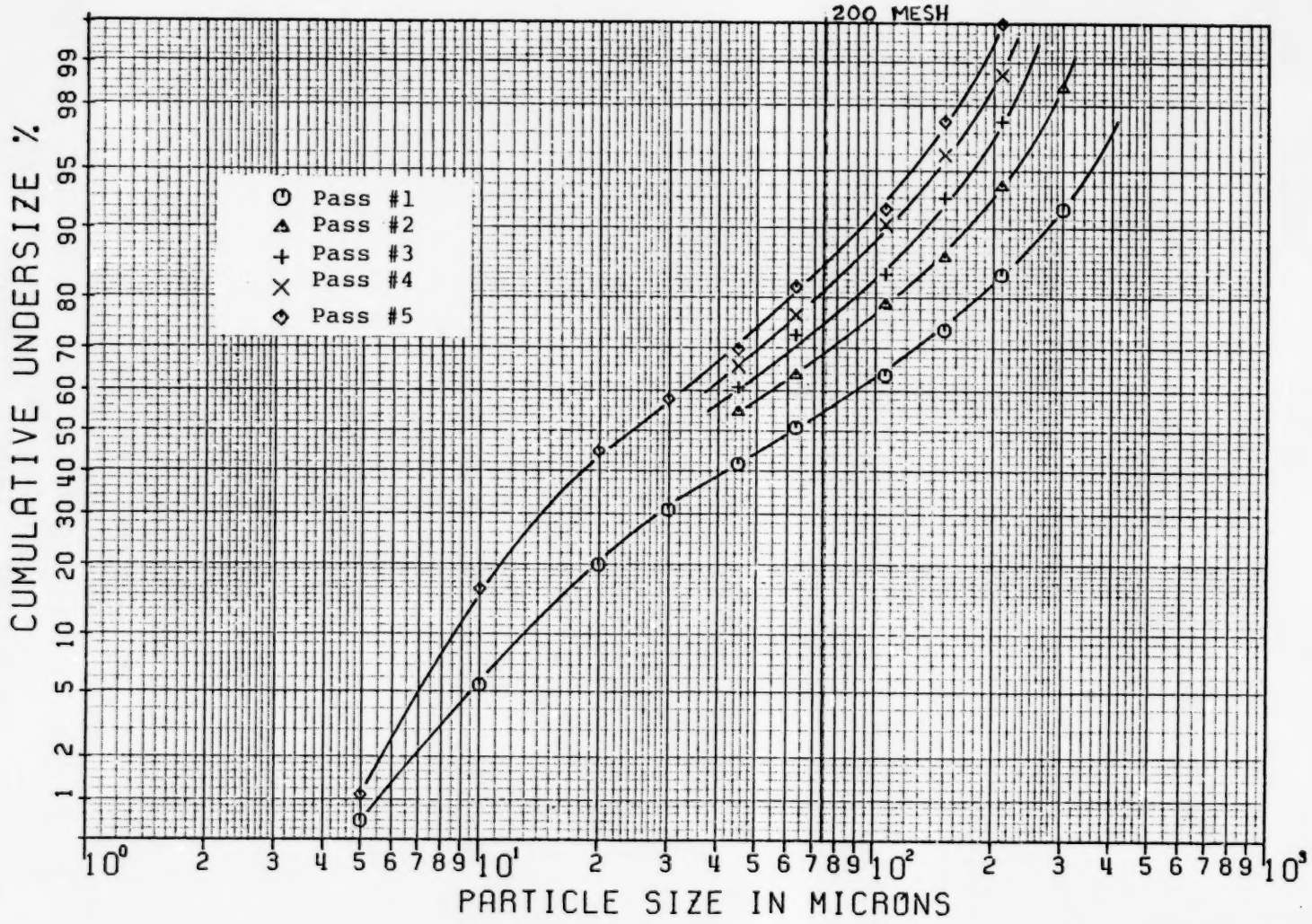


Figure 12 Particle size distributions for Pittsburgh coal ground in #2 oil; 600 rpm, 2150 kg/h of coal, four big rollers.

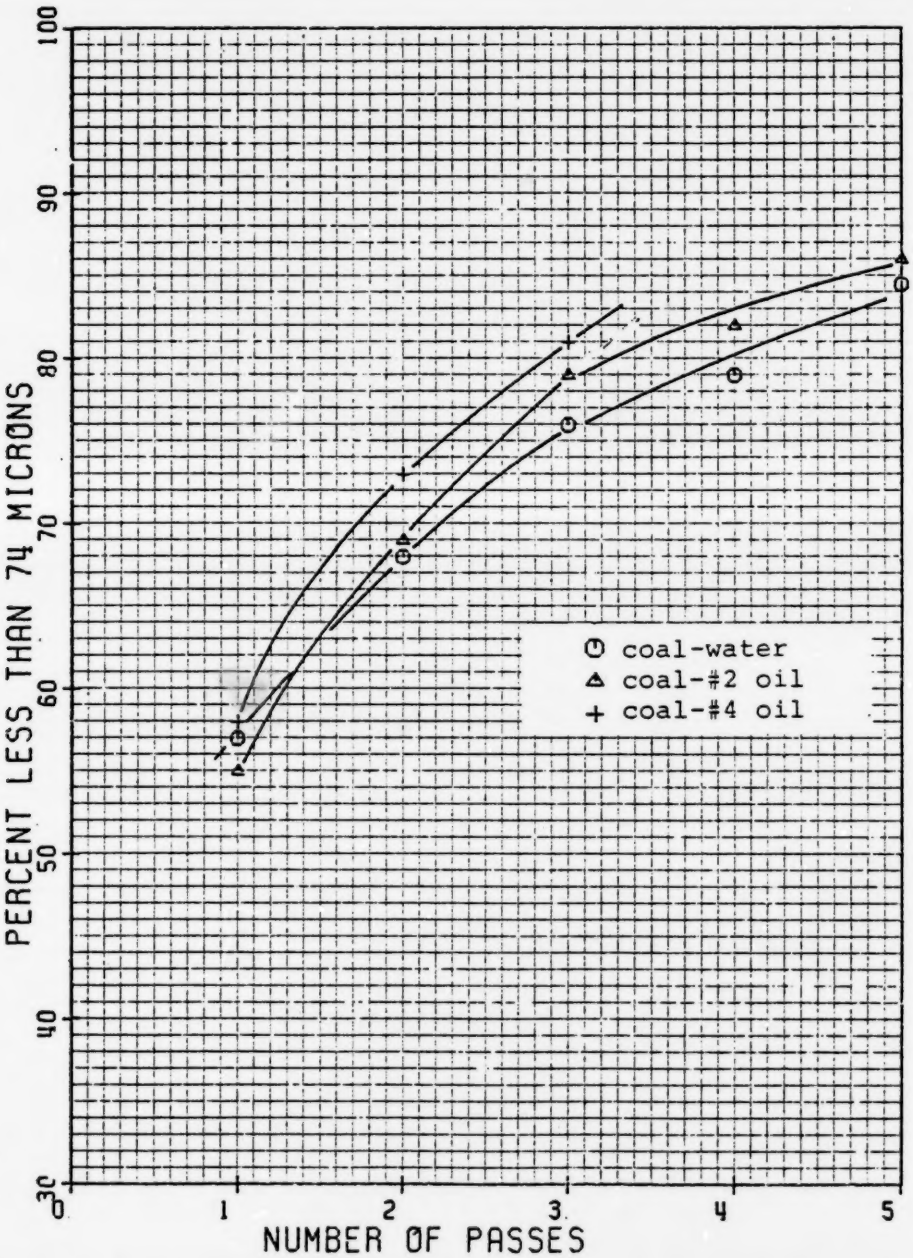


Figure 13 Variation of grinding performance with slurry medium; Pittsburgh coal in water and in #2 and #4 oils; 2100 kg/h of coal, 600 rpm; four big rollers.

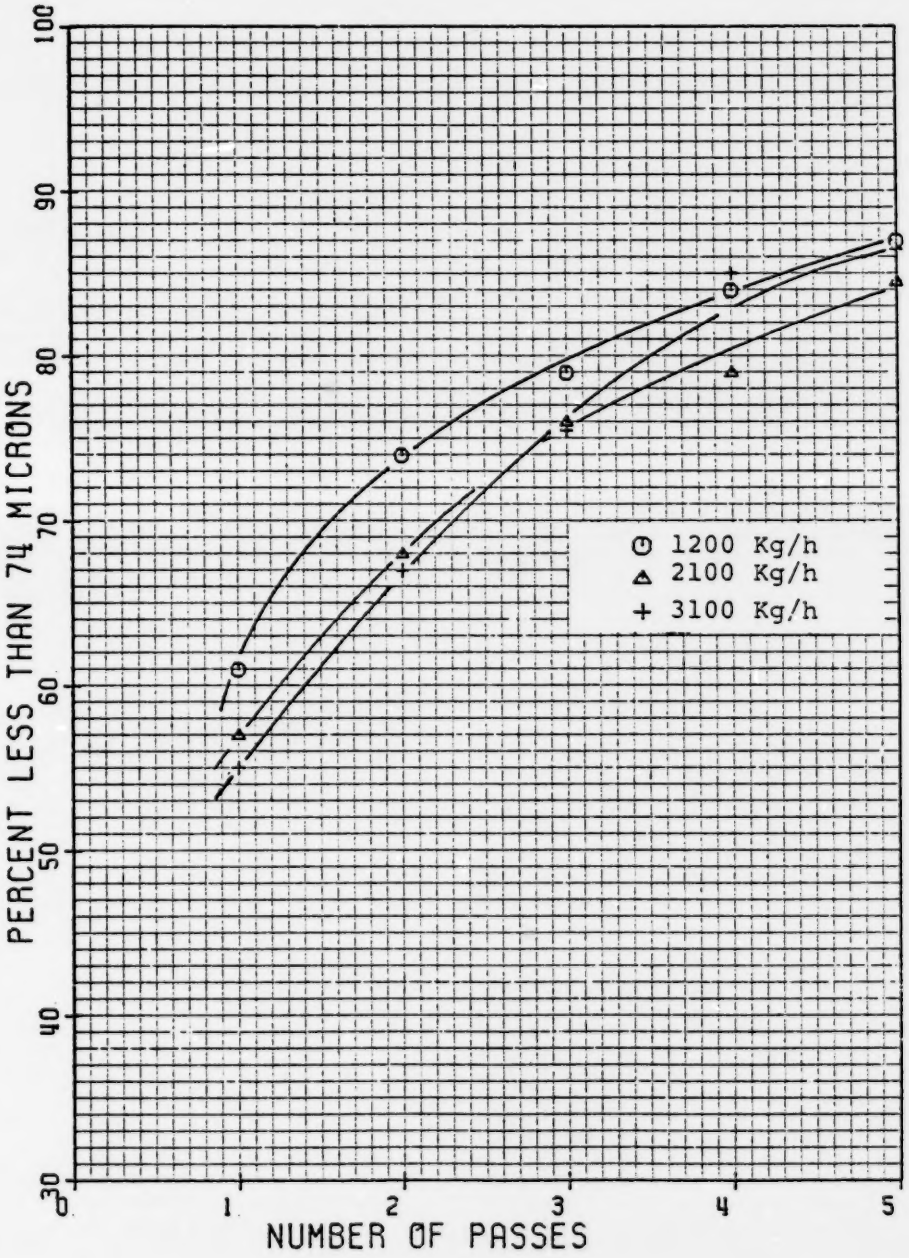


Figure 14 Variation of grinding performance with feed rate and number of passes; Pittsburgh coal in water; four big rollers, 600 rpm.

# APPENDICES

APPENDIX I



**COAL: PHOENIX OF THE '80s** - *Proceedings 64th CIC Coal Symposium - A. M. Al Taweel, editor, C.S.Ch.E., Ottawa (1982)* pp. 235-243.

# GRINDING OF COAL SLURRIES WITH THE SZEGO MILL

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## ABSTRACT

Grinding of coal in oil for COM fuel preparation is simpler and may give better slurry properties than dry grinding followed by dispersal in oil. Different coals have been ground with the novel Szego mill in oil over a range of operating conditions. When the coal has a high ash content and beneficiation is required, grinding can be carried out in water, followed by oil agglomeration of the coal particles to prepare the COM fuel.

The main design and operational features of the mill are described. Comparative performance data for grinding coal both in oil and in water are then presented. The main variables considered are single and multiple-pass operation, the rotational speed of the mill, coal feed rate, and slurry consistency. A mean particle size down to about 15 μm is readily obtained, at reasonable capacity and power consumption. Aspects of mill scale-up are discussed.

## KEYWORDS

beneficiation; coal-oil slurries; coal-water slurries; comminution; grinding, wet.

## INTRODUCTION

A great deal of practical experience about dry grinding of coal has been accumulated over the years. As a result, even where the coal is used wet, such as in a coal-oil slurry or mixture (COM), dry grinding followed by dispersal in oil is the common approach. However, significant advantages are possible when the coal is ground directly in oil for COM preparation: equipment for grinding will be simpler, particularly as explosive hazards and the need for dust control are eliminated, no separate dispersal of the dry coal into oil is required, and there is the likelihood of better slurry properties.

In dry grinding a small amount of surface oxidation of the coal is inevitable. Grinding directly in oil will allow good contact of the freshly generated surface with the oil phase. This should enhance dispersion and reduce settling.

Some of these advantages as well as concerns have been described by Luckie, et al (1). They used the tumbling ball mill which is favoured largely because it is reliable and can be scaled up to very large sizes. A comparison of different wet grinding mills was given by Hatano (2) and a recent evaluation has been made by Singh (3), but in general published data on mill performance for wet grinding in oil are rare.

When the coal to be used in the COM has a high ash and sulfur content so that beneficiation is required, grinding can be carried out in water, followed by oil agglomeration of the coal particles to prepare the COM fuel (4). Hence, grinding coal in water is no less important; in view of the recent interest in coal-water slurries as a potential boiler fuel, it may become even more so. For both of these applications, considerably finer grinding of the coal is preferable so as to better liberate the ash for agglomeration, and to improve coal-water slurry combustion characteristics. Cochran and Sell (5) have presented a convincing case for using fine coal also in COM fuels; a median particle size of about 15 μm will give good slurry stability without the need of additives, reduce abrasive wear of equipment and improve combustion. Stable coal-oil-water emulsion fuels have also been prepared and tested successfully (6,7).

In this paper, new results on grinding coal in oil and in water with the novel Szego mill are presented. This mill, shown schematically in Figure 1 is being developed for both wet and dry grinding of various materials by General Comminution, Inc., in close cooperation with the Unviersity of Toronto, and it shows good potential for COM preparation. A brief description follows.

## THE SZEGO GRINDING MILL

This mill consists principally of a stationary, cylindrical grinding surface inside which a number of helically grooved rollers rotate, being suspended by flexible wire rope shafts from flanges connected to a central drive shaft. The feed material enters at the top and the product is discharged at the bottom of the mill. See Figure 1. The particles, upon entering the grinding unit are repeatedly crushed between the rollers and the stationary grinding surface. The crushing force is created mainly by the radial acceleration of the rollers. The crushing pressure on a particle depends on the contact area between the roller, the particle, and the stationary grinding

surface. Very large crushing pressures can be obtained. The flexibility of the roller supports appears to allow the crushing force to be directed at positions where it is most needed. Another important feature is the ability of the roller grooves to aid transport of the material through the mill, thus providing a means to control residence time and mill capacity. The mill has been patented.

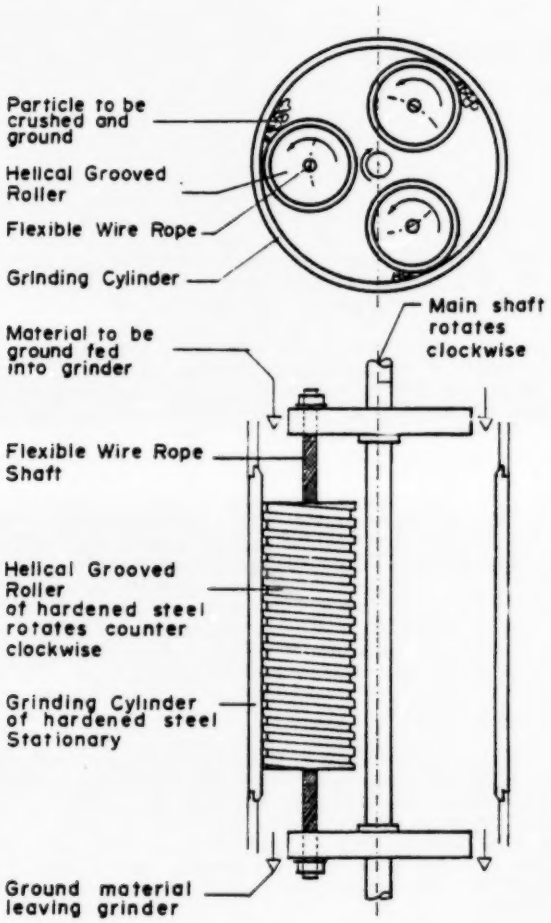
Particle to be crushed and ground
Helical Grooved Roller
Flexible Wire Rope
Grinding Cylinder
Material to be ground fed into grinder
Main shaft rotates clockwise
Flexible Wire Rope Shaft
Helical Grooved Roller of hardened steel rotates counter clockwise
Grinding Cylinder of hardened steel Stationary
Ground material leaving grinder

Figure 1. Schematic diagram of The Szego Mill.

The main design variables are the number and length of the rollers. Other important variables include the mass of the rollers and the size, shape and number of starts of the helical grooves on the roller surfaces. These and other variables allow wide design flexibility for specific applications. The mill has a high capacity, moderate power consumption, is capable of a large size reduction, and, due to the rolling action, gives preferential flaky products. Also this last feature should help improve settling behaviour of the coal-in-oil slurries.

## PREVIOUS WORK

The major previous study was carried out by Papachristodoulou (8) and has been published as Ref. (9). A 600 to 840 μm monosize Pittsburgh coal was ground in #2, #4 and #6 fuel oils at 42 weight percent solids concentration using a small Szego mill, 17 cm in diameter, with three rolles and a 12 cm long grinding surface. Mill hold-up was varied from 15 to 100% and rotational speed ranged from 220 to 1040 RPM. The coal-oil slurry was recirculated through the mill and samples were withdrawn periodically. This, then, was essentially a batch grinding operation, and data were obtained as particle size vs. average residence time at any particular operating conditions.

A typical example of the resulting particle size distributions is given in Figure 2. The coordinates of this plot may seem unfamiliar--the logarithmic and normal probability axes are used but, deviating from the conventional log-normal plots, percent passing stated size is plotted against the size. Effectively, the axes have been interchanged so that the dependent variable is plotted vs. the independent variable, in conformity with most other size distribution plotting schemes. This allows a narrow size distribution to have a steep slope, and vice versa, as is usually expected. The convenience of the log (%) vs. log (size) plot is retained without loss of information at the high percentages. As such, this way of plotting is quite similar to the Rosin-Rammler size distribution plots.

From the low residence time measurements, kinetics of monosize disappearance were obtained, and found to be 1st order in #2 oil and 2nd order in the more viscous #4 or #6 oils.

Temperature was maintained at 23°C for both #2 and #4 oils. The viscosity of #6 oil at 85°C is equal to that of #4 oil at 23°C. It should, thus, be possible to simulate grinding of hot #6 oil by using #4 oil cold. Figure 2 shows not only the progress of grinding as a function of resident time, but it also proves that, with viscosities matched, the results for #4 and #6 oils are essentially identical--note the double symbols at 2, 10, 106 and 216 second plots which are in surprisingly close agreement.

It is observed that, at 930 RPM and 30% hold-up, after 10 seconds the mean particle size is about 150 μm, after 100 seconds about 40 μm, and a median size of 10 μm is approached at around 300 seconds of residence in the mill.

In general, high rotational speeds, and low hold-ups enhanced the grinding rate. Many more data, and interpretation, are found in References (8) and (9).

## EXPERIMENTAL CONSIDERATIONS

Work was continued in a larger, 22 cm diameter mill, with three, 30 cm long, coarse-grooved rollers. With practical COM fuel preparation in mind, it was decided to operate in a continuous grinding mode, or to simulate continuous grinding in multiple passes, rather than to grind in the batch mode.

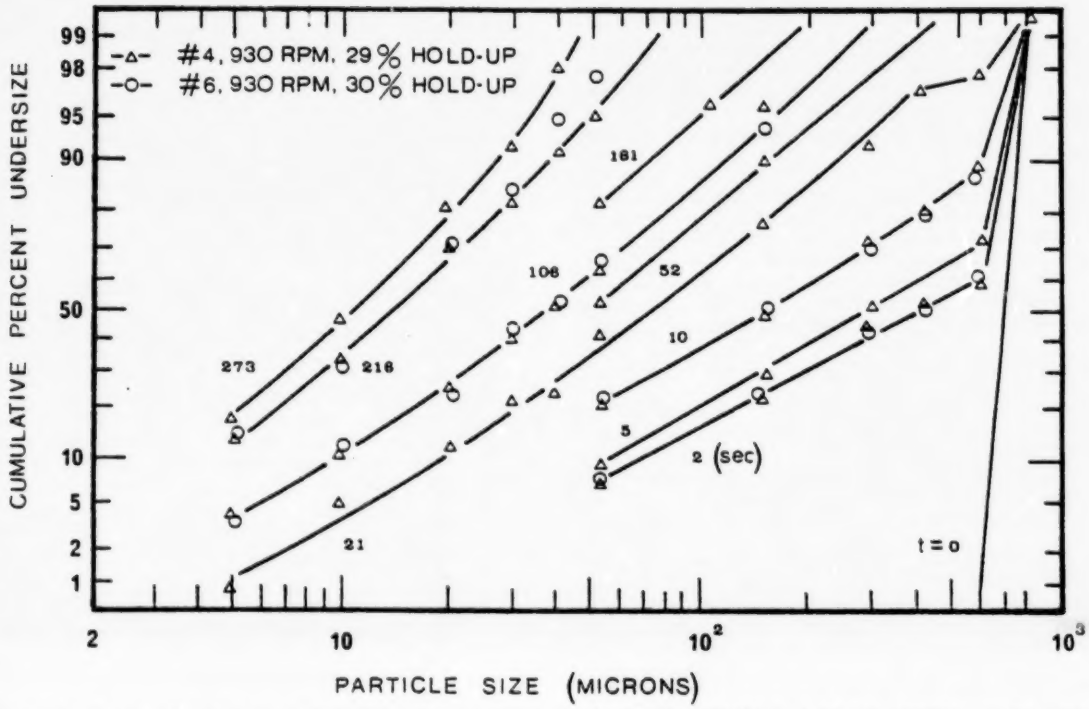


Figure 2. Size distribution as a function of time for coal in #4 oil (23°C) and #6 oil (85°C); small mill, 42 weight percent Pittsburgh coal.

Control of hold-up in the larger mill turned out to be difficult; gravity flow of the relatively fluid slurry in the mill was so rapid that slurry residence time in any one pass was very short, so little grinding was accomplished and many passes would be required. Since continuous operation with many passes was obviously impractical, it was decided to reduce the effect of gravity by switching to more viscous slurries which could not flow so freely. As viscosity increases rapidly with solids concentration, this was easily accomplished.

The results, when grinding in this "paste" mode were surprisingly good. Not only was the residence time increased, as expected, but the amount of grinding accomplished in a pass increased several-fold more. Transport through the mill was now minimally influenced by gravity and controlled almost completely by the conveying action of the helical grooves on the rollers. It was found that there is a desirable fluid consistency range for best operation, considering the extent of size reduction, throughput, ease of operation, and power consumption.

For coal and water, the desired paste consistency was obtained in the solids concentration range of 60 - 65% by weight. With oil, a somewhat higher concentration, of about 65% coal worked best.

## Materials

The illustrative data presented later were obtained with three different coals, viz. bituminous Pittsburgh coal, Minto coal from New Brunswick and Luscar (Coal Valley) coal from Alberta. The media used were water and #2 and #4 fuel oils, with the expectation that #6 fuel oil at high temperatures would behave reasonably similarly to the cold #4 oil.

These coals are physically quite different. The Pittsburgh coal is of a medium hardness, contains 8% ash and has a Hardgrove grindability index of 55 - 65. The Minto coal is very hard, has virtually no fines, an ash content of 28%, and a Hardgrove index of 60 - 65. The Western coal is the opposite, very soft, with a lot of fines, 10% ash, and a Hardgrove index of 45. The coals were initially crushed to -3/4 inch but for later work, a -1/2 inch screen was used.

The two base oils had viscosities of 3.8 cS for #2 and 21.3 cS for #4 oil at 40°C. The experiment were carried out at room temperature with no particular control steps or precautions taken except for a cooling jacket around the mill. At a typical starting temperature of 23°C the viscosities were 6.3 and 38 cS, respectively.

## Operating Conditions

Experiments were carried out, in most instances, over the following ranges of conditions:

Feed rate: 400, 800 and 1200 kg/h of coal
Rotation speed: 1200, 1500 and 1800 RPM
Number of passes: 1, 2 and 3, sometimes more

Mill hold-up and residence times were not measured; the latter are estimated at 10 - 30 seconds per pass,

varying approximately inversely with both feed rate and rotational speed.

All experiments reported here were carried out in the "paste" mode of operation, 60 - 65% by weight coal in water, or 63 - 68% coal in oil. Data for one internal mill configuration only are reported: three rollers, each 30 cm long, with a coarse, single-start helical groove structure.

After each pass, the particle size distribution was measured as described below. The amperage to the motor was recorded for each run. Power drawn during a run and the specific energy consumption in kWh/ton were calculated. The reported values include motor and variable speed drive losses; actual power delivered to the mill may well be 15% lower than the reported values.

## Particle Size Analysis Technique

Samples were initially analyzed by wet sieving for the coarse fractions and by using the HIAC PC-320 analyzer with the CMB 60 sensor head for the fine material below 60 µm. The method, described in (8) and (9) is relatively laborious. For coal-water work, the washing steps with varsol and detergent were, of course, not necessary.

Later, a larger sensor (CMH 300), usable up to 300 µm size was acquired for the HIAC Instrument. Wet sieving was then used only to measure the fraction of material above 300 µm, if any, and the fraction above 60 µm, with a 63 µm standard sieve. That value was used to tie the two HIAC analyses together. The smaller sensor covered the range from 2 - 63 µm in five increments, and the bigger one was gated to range from 63 - 300 µm, in another five increments. The small fraction of material below the 2 µm detection limit was neglected.

With the smaller sensor, an adequate number of counts was obtained with only part of the sample running through the sensor. With the larger sensor and a significant fraction of rapidly settling particles, the total diluted sample was always analyzed so as to avoid any error caused by settling during analysis. All coal-oil data reported in this paper were analyzed with the dual sensor system.

## RESULTS AND DISCUSSION

The size distributions given in Figure 3 for the grinding of Pittsburgh coal in water illustrate in a qualitative manner all key operating variables. The feed size has, for all cases, been -3/4 inch x 0, far beyond the size coordinate of the figure.

Starting with the coarsest product, the curve on the extreme right gives the first pass result for the intermediate rotational speed of 1500 RPM at the highest feed rate, 1200 kg/h of coal. The total coal-plus-water feed is 2000 kg/h, two metric tons through a 23 cm diameter mill in an hour. Even at that rate, the product is reasonably fine, with a median size (taken to be the 50% value by weight) of 54 µm and 58% passing 200 mesh (74 µm), or, as used in later figures, 42% > 200 mesh. For a median feed size of about 5 mm, this corresponds to a 100-fold reduction in size.

For the next curve, the coal feed rate is changed from

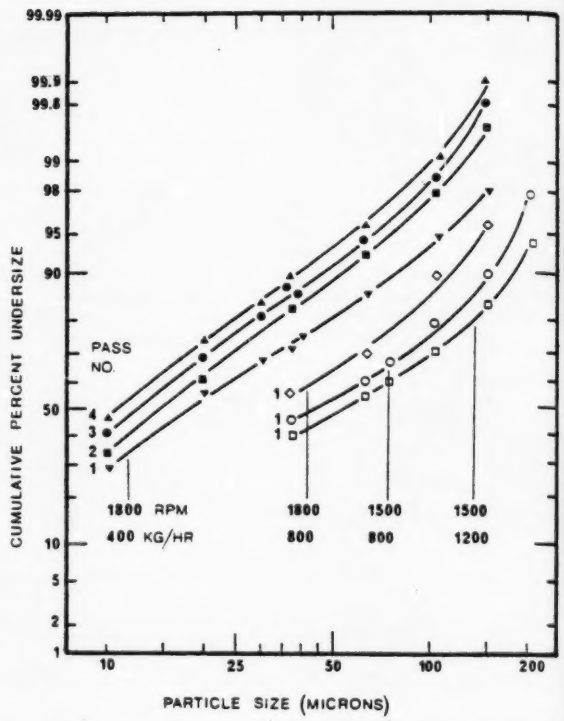


Figure 3. Size distributions for grinding in water at various conditions; 22 cm diameter mill, 60 - 65 weight percent Pittsburgh coal.

1200 to 800 kg/h and the product is correspondingly finer, 44 µm median size, with 33% > 74 µm. For the third curve, the feed rate is kept constant and the rotational speed increased from 1500 to 1800 RPM. The resulting product is again finer, with a median size of about 30 µm and 80% passing 200 mesh, i.e., the standard utility-boiler fuel particle size.

The finest products are obtained at the high, 1800 RPM speed and the lower feed rate of 400 kg/h. The previous three products were wet-sieved so the size analysis extended down to 37 µm. The still finer ones have also been analyzed with the HIAC counter for the -63 µm size cut.

The median size for the first pass is now down to 18 µm with almost 90% passing 200 mesh. The subsequent 2nd to 4th passes of the same material through the mill, each shown individually, reduce the mean size to 11 µm, in approximately equal increments on the logarithmic scale. It is obviously getting more and more difficult to reduce the size further. This mill configuration is reaching its limiting size. It should be added that with a different, triple-start groove design, and the same operating conditions, this finest size was attained in 2 passes, with a cumulative specific energy requirement of 74 kWh/ton.

## Grinding in #2 Oil

The data reported in this subsection were obtained with Pittsburgh coal crushed to -1/2 inch x 0 and fed

to the mill at a solids concentration of about 65%. The feed rates refer again to kg/h of coal rather than to coal plus oil. The mill and the materials were initially at room temperature, in the 20-25°C range. The cooling jacket removed much of the heat, but there was a noticeable temperature rise during passage of the material through the mill. This ranged from a few degrees for low rotational speeds and high feed rates to about 50 degrees at the highest RPM and low feed rates. At these highest temperatures, there was some evaporation loss of #2 oil which had to be replaced for the 2nd and 3rd pass experiments.

During any one run, temperature was rising slowly with time as the mill absorbed some of the liberated heat and moved through a thermal transient toward a steady state condition. About 45 kg of coal was used in most experiments, giving test times of 2+ to 7 minutes. This meant that the thermal steady state was approached closely only during the low feed rate runs and reached only in a few particularly long experiments. The effect of this on grinding performance should be minor.

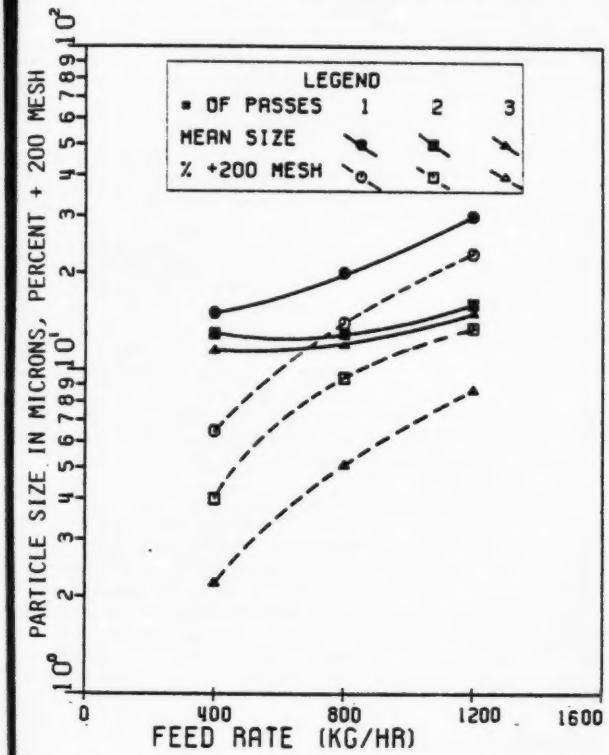


Figure 4. Median particle size and percent +200 mesh (> 74 μm) vs. coal feed rate; 1800 RPM, 65 weight percent Pittsburgh coal ground in #2 oil.

Figures 4 and 5 give summary results for Pittsburgh coal over the full range of operating conditions. The ordinates give the median size in microns, and also the percent of coal remaining above 200 mesh, on the same scale. In Figure 4, the independent variable is the feed rate with the rotational speed fixed at 1800 RPM. In Figure 5, feed rate is fixed at 400 kg/h and

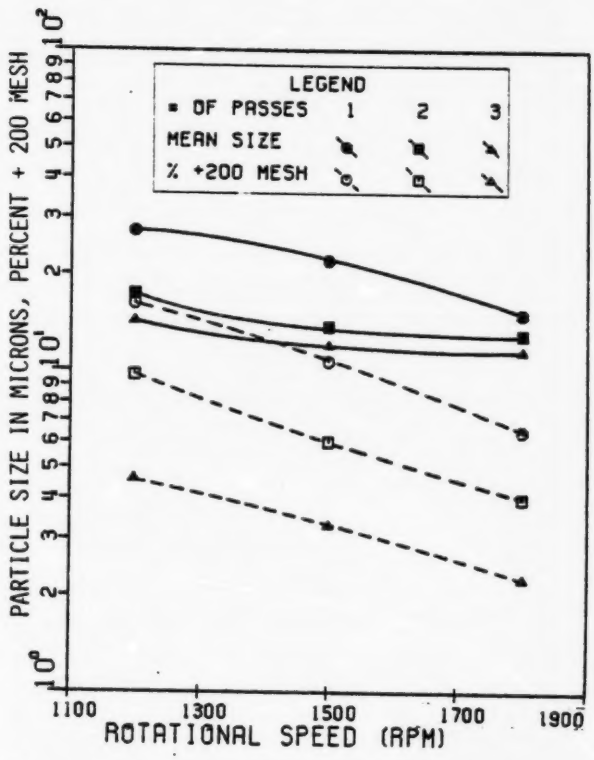


Figure 5. Median particle size and percent +200 mesh (> 74 μm) vs. rotational speed; 400 kg/h Pittsburgh coal ground in #2 oil.

RPM is plotted on the abscissa. Both graphs give the 1st, 2nd and 3rd pass as parameter.

As in the previous coal-water case, it is observed in Figure 4 that the highest feed rate gives the coarsest products. There is a big change in the median size with feed rate for 1st pass results, from 30 to 15 μm, whereas in the 2nd and 3rd passes, the change with feed rate is minimal, only from 15 to 11.5 μm in the 3rd pass. This indicates that a limiting size, for this mill configuration in the 10-12 μm range is being approached and neither higher speeds nor lower flow rates will make the product much finer. Yet, the percent +200 mesh is changing steeply, showing that the coarse end of the size distribution continued to be ground finer. Actually this change is overemphasized on the logarithmic scale for low numbers.

Similar observations can be made for Figure 5. The median size of the first pass products is dropping significantly with RPM, with only minimal changes in the median size observed for the very fine 2nd and 3rd pass products. The coarse end is ground finer with RPM and number of passes. At the highest RPM of 1800, the product is ground so fine already in the first pass, down to 15 μm, that there simply is not much room left for further improvement.

Other cross-plots at different RPM's and feed rates show similar trends; only the approach to the limiting

size is not as strongly emphasized for high feed rate-low RPM combinations; changes in mean size per mass remain higher.

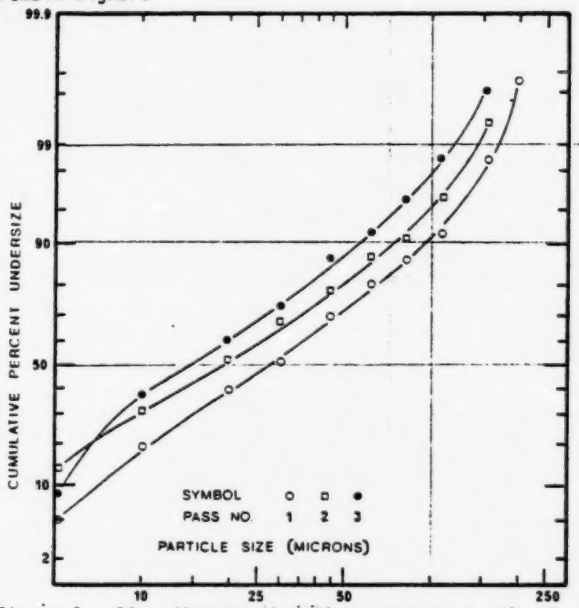


Figure 6. Size distributions for grinding in #2 oil; 1200 RPM, 400 kg/h, 1, 2 and 3 passes.

The full particle size distributions are shown in Figure 6 for one set of Figure 5 data, namely those at 1200 RPM and 400 kg/h coal feed rate. The crossover of 2nd and 3rd pass data is not real, but reemphasizes the fact that additional passes do very little to material which has already been ground extremely fine. Both measurement inaccuracy and particle agglomeration may influence those very small particle size data.

## Grinding of Different Coals

Similar extensive sets of data have also been obtained with the Minto and Luscan coals. A close comparative look shows the Pittsburgh and Minto data to be practically identical. This may really be expected from their similar Hardgrove index values, in spite of the very significant differences in physical appearance. Thus, results in the previous section apply equally well to Minto coal. The Luscar coal does show at least a small difference--it is always slightly coarser than the other ones. The effect is just noticeable, but consistently so, at low feed rates and increase as the mill is loaded more heavily.

Figure 7 gives size distribution data for both the Minto and Luscar (Coal Valley) coals at the highest feed rate of 1200 kg of coal per hour and a rotational speed of 1800 RPM. Pittsburgh coal curves, for all three passes virtually overlap the Minto curves. The observed difference in the median size is 10 μm for the first pass, and falls to about 3 μm for the third pass. At lower RPM's and the same feed rates, the differences would be slightly greater; this set of data was chosen for clarity, to minimize overlap.

What these and other similar results indicate is that

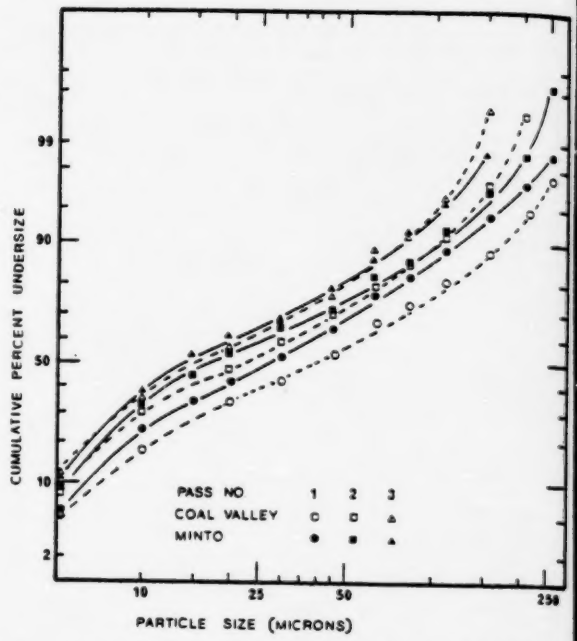


Figure 7. Comparison of Luscar (Coal Valley) and Minto coal particle size distributions; 1800 RPM, 1200 kg/h of coal in #2 oil, for 1, 2 and 3 passes.

differences in the grindability or other physical characteristics of the coals do not make quite as large a difference in the Szego mill as one might expect, at least not in the "paste" grinding mode for fine sizes. To quote some numbers which could crudely be compared with the Hardgrove index, after the first pass, at 1200 kg/hr and 1500 RPM, 54% of the Alberta coal passes 200 mesh, with the corresponding figures for the New Brunswick and Eastern U.S. coals being 60 and 62%, respectively. The corresponding numbers from Figure 7 are 70% (Alta.), 80% (N.B.) and 77% (U.S., not shown).

Also note in Figure 7 that, at the fine end, the difference between the 2nd and 3rd passes is minimal, as observed previously. The very fine particles either are not ground further, or agglomerate at a comparable rate, or a combination of these possibilities may apply. At the coarser end, the incremental changes from 1st to 2nd, and from 2nd to 3rd pass are roughly comparable, or slightly greater for the Alberta coal.

## Grinding in #4 Oil

Data presented here should be taken to represent, at least roughly, also grinding of coal in #6 oil, as shown for the well-controlled temperature conditions in Figure 2. Since the temperature-viscosity relationship for both #4 and #6 oils is similar, any heating which takes place during an experiment is likely to have approximately similar effects; it will be seen soon that differences between grinding in #2 or #4 oil in this paste mode are not really large, leading further credence to the expectation that base oil viscosity variations are not really predominant.

A comparison, this time for Minto coal, ground in #2 and #4 oils, is made in Figure 8. The median size and one set of % > 200 mesh data are shown for feed rates of 400 and 1200 kg/h, at 1800 RPM, plotted against number of passes. Other data have been omitted to avoid overlap of curves.

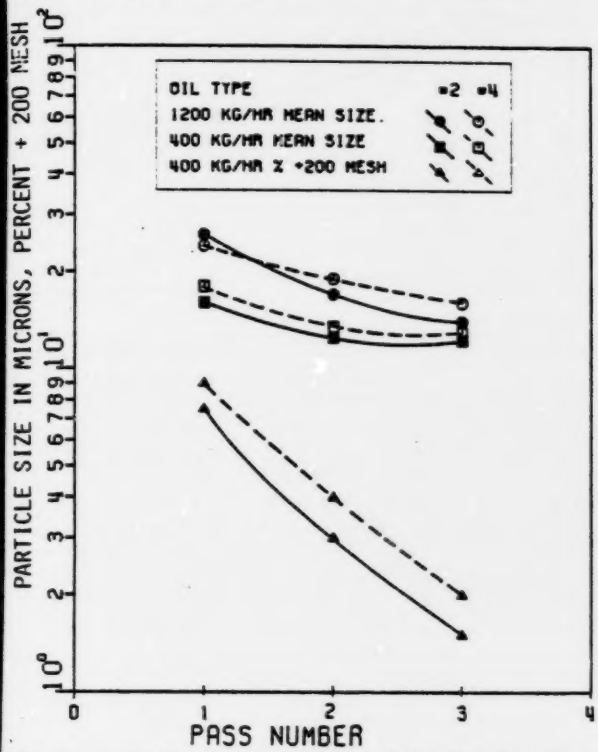


Figure 8. Comparison of grinding in #2 and #4 oils; median particle size and percent +200 mesh (> 74 μm) vs. no. of passes; 1800 RPM, Minto coal.

It is apparent that the 6-fold change in base oil viscosity has not made a major difference. Median sizes are, typically, 2 - 3 microns higher in #4 oil, a difference barely larger than experimental error. As in this figure for the two highest points, there is occasional cross-over observed also with other data, so Figure 8 is a good representation. At low RPM's where the products are coarser, some differences are slightly larger.

It will be shown later that the larger and more important difference caused by base oil viscosity comes in power consumption.

## Energy Requirements

Measurement of power consumption is more susceptible to errors than getting representative samples of the products and analyzing these carefully. The mill does not work in a steady manner but there is considerable continuous oscillation in the amperage drawn, likely caused by momentary variations in feed rate and mill hold-up. The reported data have been obtained by approximating an average value by eye. It was also observed in a few, late long-duration experiments that power consumption in the beginning of a run, for the first few minutes was higher, be perhaps 20% or even more, than the stabilized value for long times. A plausible explanation is the thermal transient caused by the slow heating of the mill as it approaches the thermal steady state much later than required for reasonably established grinding conditions. As viscosity is reduced, power consumption should also fall.

The power consumption per pass is practically constant for any one set of conditions. At 1200 RPM and 400 kg/h feed, for the grinding of Pittsburgh coal in #2 oil, the specific energy consumption in kWh/ton was 30.3, 31.4 and 31.5 for 1st, 2nd and 3rd pass, respectively, giving the product size distribution shown in Figure 6.

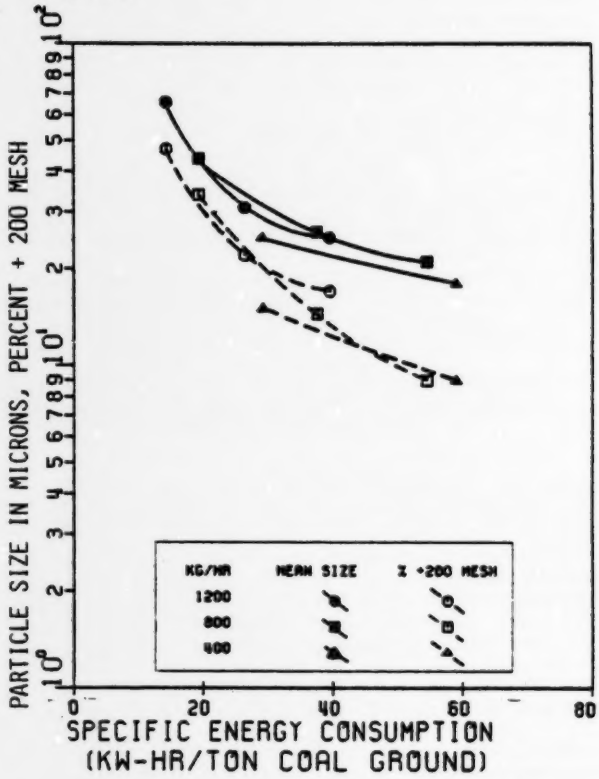


Figure 9. Specific energy consumption for different median sizes and percentages +200 mesh (> 74 μm); 1200 RPM, Minto coal.

The median size of a product can be related to the cumulative specific energy consumption required to attain that size, and thus data for all individual experiments and conditions can be summarized. This has been done in Figure 9 for Minto coal in #2 oil at 1200 RPM, with the familiar median size and % > 200 mesh on the ordinate and kWh/ton on the abscissa. The particular data shown are fairly typical, with considerable scatter or deviations shown for the different conditions, i.e., feed rates and passes.

It is observed that for size data, on the upper curve, both the 800 and 1200 kg/h rates coincide, and a smooth

curve is obtained with the six points respresenting three passes for each. From other observations one would expect the energy efficiency to drop as one goes to lower feed rates, i.e., lower loading of the mill. The 400 kg/h rate curve, while parallel with the upper one, is actually below it, indicating a finer product for the same specific energy consumption, or a lower specific energy consumption, for an equally fine product, this contrary to expectation.

The likely reason for this behaviour is that, since the high speed rate runs were very short, about 2 minutes at 1200 kg/h, power measurements were taken during the early, cooler portion of the transient, whereas, particularly for the low, 400 kg/h feed rate, the run was long enough to allow the measurement to be taken close to the developed thermal steady state condition when power consumption was lower. Typically, the amperage drawn was observed and recorded during the second half of a run.

Other data show that the specific energy consumption for the same fineness does also not change much with RPM; the increased power drawn at higher rotational speeds is balanced by getting a finer product. It may be that the higher crushing forces at higher RPM's indeed act so efficiently, or, that due to the greater dissipation of heat the thermal transient was shorter and the amperage was measured closer to the warmer, steady state condition, with its resultant power saving.

The implication of the above for specific energy requirements is that most of the data slightly over-estimate it for sustained operation, particulary so the values obtained at high feed rates and low rotational speeds.

The lower group of curves, for % > 200 mesh, shows, typically, more scatter, since the results as plotted are really too dependent on just a tiny shift in the size distribution curve.

Otherwise, the trends are similar. Perhaps a wide, smooth curve could be drawn through the data, more-or-less following the intermediate, 800 kg/h curve, a little lower in the beginning. It would show 27 or 28 kWh/ton required to get an 80%-200 mesh product, the standard utility boiler grind, and 50 kWh/ton for 90%-200 mesh. With the cooling jacket off, both viscosities and power consumption would have been lower.

The Alberta coal was ground slightly coarser. Specific energy consumption data are shown in Figure 10, again for 1200 RPM operation and on the same basis. Comparison shows that at least for median size, the power consumption in each run is reduced correspondingly. The size vs. specific energy curves overlap with the Minto curves of Figure 9, which figure also represents Pittsburgh coal quite well.

Figure 10 shows two additional dashed curves. These are for #4 oil (mean size only), and show an increased energy need for the more viscous oil. In this figure, the 400 kg/h data are in better agreement with the others. On an average, #4 oil power consumption rates exceedes those in #2 oil by a factor of 1.5.

The products, when checking individual data points, i.e., number of passes in Figure 10, were also slightly finer, makeing the important difference smaller, more-or-less as shown in Figure 10.

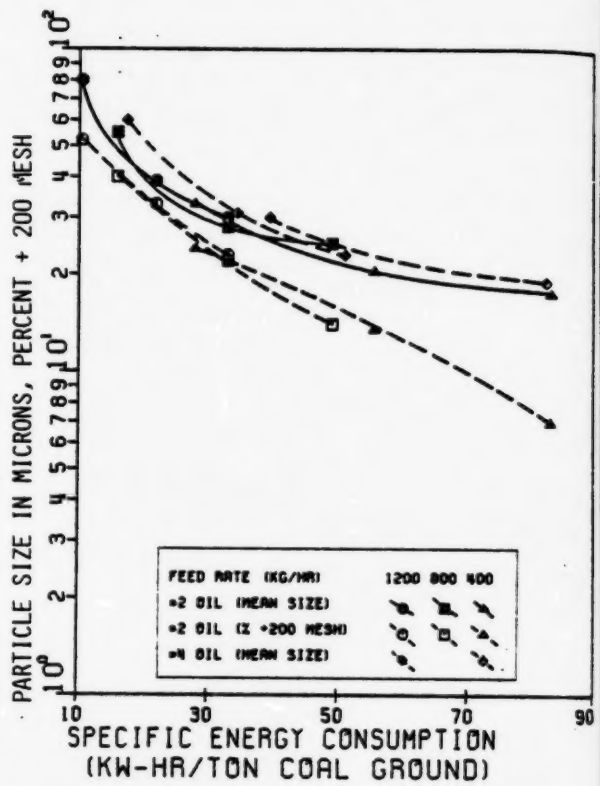
PARTICLE SIZE IN MICRONS, PERCENT + 200 MESH
SPECIFIC ENERGY CONSUMPTION
(KW-HR/TON COAL GROUND)
FEED RATE (KG/HR) 1200 800 400
#2 OIL (MEAN SIZE)
#2 OIL (% +200 MESH)
#4 OIL (MEAN SIZE)

Figure 10. Specific energy consumption for different median sizes and percentages +200 mesh (> 74 μm); 1200 RPM, Lascar (Coal Valley) coal ground in #2 and #4 oils.

## OPERATIONAL ASPECTS AND SCALE-UP

The data reported in this paper, all obtained with one set of mill internals, suggest a number of possible trade-offs. For example, one could operate the mill at various combinations of feed rate and rotational speed to meet the same product specification, one could run several passes at a high feed rate, or only one at a low feed rate at the same RPM, etc. Generally, loading the mill highly and running it at a low RPM is more favourable, with energy savings not clearly shown in these data) and reduced mechanical strain and wear associated with high-speed operation.

Brining in also design variables, for example different groove arrnagements, will greatly increase the number of available options in optimizing mill performance for any desired product specifications. For example, a multistart helical groove structure will increase transporting capability and reduce mill hold-up. A finer groove structure should reduce the limiting particle size by allowing closer approach of the rollers to the cylinder wall. Multistage operation with different roller designs in different sectins is an interesting possibility. Some of these alternatives have been explored briefly but much remains to be done.

The question of mill scale-up has received considerable attention, and two eventually converging approaches have been taken. The more empirical one relies on proper correlation of performance data from differently sized units, in effect establishing the importance of size-dependent design parameters by experimental measurement. The other approach relies on mathematical modelling of both mill performance and the dynamics of fluid flow, crushing and shearing phenomena, and their dependence on design and operational parameters.

A test program with a larger, 44 cm diameter mill has just started. Once this larger mill proves itself, it will be available for commercial use, and during the testing phase it will provide data both for empirical scale-up and for checking our performance and dynamic modelling results. In principle, there are no difficulties in scaling up the Szego mill. Indeed, better performance and easier resolution of mechanical concerns are foreseen.

This mill is not yet is sustained commercial operation. Several mills are being tested in industry, but reliable information on wear, maintenance and related operational questions is minimal at this time. Sustained use of some mills is imminent in several applications, including wet grinding of coal and will provide important answers to these questions.

Work on the characteristics of coal slurries prepared with the Szego mill is also progressing. Data on the rheological behaviour of ultrafine coal-oil mixtures have just been presented (10). Work is in progress extending these results to more coarsely ground slurries, as well as on the stability of such slurries.

## SUMMARY AND CONCLUSIONS

Experiments were carried out in a 22 cm diameter mill equipped with three 30 cm long rollers, coarse-grooved in a single-start helical pattern. The rotational speed range was 1200 - 1800 RPM. Coal feed rates varied from 400 - 1200 kg/h, giving total coal and liquid feed rates from 600 - 2000 kg/h. Summarizing:

- In a single pass, typically 50 - 90% of the coal is crushed to -200 mesh (< 74 μm).
- In multipass operation, a 12 - 20 μm median size is readily obtained in 2 - 3 passes through the mill.
- The benefit of grinding beyond a 2nd or 3rd pass is minimal; a limiting size of 10 - 12 μm is apparent with the rollers used.
- High rotational speed and low feed rate enhance the rate of grinding.
- The differences between the grinding results with different coals and in different media were minor compared to large difference in physical characteristics of the coals and viscosities of the liquids.
- Typically the specific energy consumption for bringing the coal to 80% passing 200 mesh in #2 oil is 25 - 40 kWh per ton of coal, with slightly lower values in water and higher values in #4 oil (or hot #6 oil).
- For a 15 μm median size product, the corresponding values are 50 - 80 kWh/ton of coal.
- At optimized operating conditions the specific energy consumption should not exceed the lowest values reported above.

It may be concluded that the Szego mill is able to grind coal in water or oil down to very small sizes rapidly and efficiently. The resultant particle size distributions are relatively narrow. Following scale-up and further operating experience with the mill, it appears well suited for the preparation of coal slurry fuels.

## ACKNOWLEDGEMENT

Thanks are extended to Ontario Hydro and Gulf Canada for supplying some of the coal and oil, respectively. A mill scale-up contract from the Department of Supply and Services to General Comminution Inc., sponsored by the Department of Energy, Mines and Resources has provided partial support for the experimental work.

## REFERENCES

1. Luckie, P.T., Fletcher, G.N., Bagga, P.S. and Lau, T.L., On the Grinding of Coal in Oil. Proc. First Int'l. Symp. on Coal-Oil Mixture Combustion, Blake, J.C. and Sabadell, A.J., Editors, The MITRE Corporation, McLean, Va., p. 197, 1978.
2. Hatano, M., EPDC COM R&D Laboratory Tests and Pilot Plants, ibid., p. 113, 1978.
3. Singh, V.P., Boiler Ignition with Coal/#2 Oil Mixtures, Report. No. 81-91-K. Ontario Hydro Research Div., Toronto, 1981.
4. Capes, C.E., McIlhinney, A.E., Keever, R.E. and Messer, L., Application of Spherical Agglomeration to Coal Preparation, paper presented at Coal Preparation Congr., Sydney, Australia, 1976.
5. Cochran, J.W. and Sell, F.R., Progress in Developing Ultrafine Coal-Oil Mixtures, Proc. 2nd Int'l. Symp. on Coal-Oil Mixture Combustion, Beanstock, D., Editor, Pittsburgh Energy Techn. Center, U.S. Dept. of Energy, 1980.
6. Poetschke, L., Liquicoal Demonstration Project, paper presented at the 3rd Int'l. Symp. on Coal-Oil Mixture Combustion, Orlando, FL, 1981.
7. Hawkins, G.T., Commercial COM Operation, an Update, ibid, 1981.
8. Papachristodoulou, G., Grinding Coal in Oil with The Szego Mill, M.A.Sc. Thesis, Department of Chemical Engienering and Applied Chemistry, University of Toronto, 1979.
9. Trass, O. and Papachristodoulou, G., Grinding of Coal-in-Oil Slurries with the Szego Mill, Proc. 2nd Int'l. Symp. on Coal-Oil Mixture Combustion, Beanstock, D., Editor, P.E.T.C., U.S. Dept. of Energy, 1980.
10. Papachristodoulou, G. and Trass, O., Rheological Properties of Ultrafine Coal-Oil Mixtures, paper presented at the 3rd Int'l. Symp. on Coal-Oil Mixture Combustion, Orland, FL, 1981.

APPENDIX II

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# PREPARATION OF COAL-OIL MIXTURE FUELS

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## Abstract

COM fuels are usually prepared by dry grinding the coal and dispersing it in oi . An attractive alternative is wet grinding directly in oil, or in water with subsequent oil agglomeration to beneficiate the coal. Other proposed fuels are coal-oi - water or methanol and coal-water mixtures. Slurry stability, rheology and combusti n characteristics determine its utility in boilers.

## Introduction

It is important both from an economic and also from a strategic point of view t reduce our oil consumption. An attractive way to do this is to replace oil by pum - able coal-oil mixtures (COM) as utility and industrial boiler fuel. This would all oil savings of up to 40%, and, since retrofitting problems of such boilers are modest, implementation can be rapid and economical. This is particularly importan on the Atlantic Coast in North America where much of the electricity is generated by burning bunker oil in utility boilers. The economics of conversion are most attractive and as the price of oil continues to outpace that of coal, will become increasingly so.

It was reported in 1978 that a cost differential of $1 per million BTU between oil and coal was required to make conversion attractive (1). That cost differentia has in the last three years grown so large that oil may price itself completely ou of the utility boiler market. The alternatives are now i) to convert to coal-oil mixtures -- most convenient and rapid implementation is possible, (ii) to convert completely to coal -- far more expensive and time consuming, but with the lowest future fuel costs, or (iii) to convert to coal-water mixtures - these may be more difficult to burn, but again much cheaper than coal-oil mixtures. A great deal of additional research, development and demonstration work is required for this newes alternative. However, should a real shortage of oil develop, such as may be cause by an embargo, many utilities may be forced to burn coal-water mixtures, or be shu down.

We will consider major requirements of coal slurry fuels, briefly review the al ternatives and then discuss each of these individually, with emphasis on preparatio techniques. We will also look at the need to beneficiate the coal, combustion characteristics of the resultant mixtures and their properties, rheology and stabi lity. Possible strategies for fuel preparation and conditions which influence these strategies will complete the paper.

## COM Fuel Requirements

The most important requirements of coal slurry fuels are that they be pumpabl and readily atomized in the furnace. This essentially determines slurry rheology and the required pressure for any atomizing nozzle design to give a fine enough dispersal. Good combustion characteristics, flame stability and sufficiently rapi burning to give complete combustion during the short resident time, typical of boi lers designed originally for burning oil are also important and require the particl size to be relatively small. The ash and sulfur content must be low enough to avoi

particulate build-up inside the furnace and excessive emission in the stack gases. This may entail coal beneficiation. Another advantage of clean, beneficiated coal is that it gives a higher fuel value to the mixture and, hence, allows a larger oil replacement or gives reduced boiler derating.

Relatively serious erosion problems have been encountered in some applications, both with COM handling equipment, pumps, valves, etc. and with atomizing nozzles (2). Aside from cleaning the coal of its abrasive ash constituents, reducing the particle size will also help reduce such erosion. Settling of the COM should be avoided particularly if storage tanks and long transfer lines are used. This will entail using additives to increase slurry stability or to grind the coal finer so that its settling rate is reduced. Higher concentrations also reduce settling.

## Alternative Coal Slurry Fuels

After two dormant decades, interest in coal slurry fuels reappeared in the 1970's. The first candidate fuel was ground coal dispersed in oil (3,4). Later, coal-oil-water mixtures were proposed. They have been successfully tested and commercial production has started (5,6). Coal-oil-methanol fuels have also been proposed (7). These fuels would eliminate the heat load required to evaporate the water, and the methanol will instead provide fuel value. The latest proposal, largely brought on by the immense recent rise in oil prices is that of coal-water mixtures (8). The higher water penalty would simply be paid by using more coal but the fuel would still be considerably cheaper than the oil-based fuels. Greater boiler derating would be experienced.

The choices of these combinations will be further influenced by the possible need to beneficiate the coal, and by the beneficiation technique to be utilized. If, for example, oil agglomeration be used, it will be necessary to disperse the coal first in water and then absorb it in oil which means retaining a certain amount of water in the COM product. Each has its advantages and disadvantages, and invariably economics must be considered in the light of the particular conditions of a region or source of raw materials or possible business incentives. A more detailed look follows.

## Coal-Oil Mixture (COM) Fuels

Several demonstration projects have been or are in operation burning coal in #6 (bunker) oil. The various technical problems associated with COM preparation and combustion have been examined and the technology required to implement COM fuels usage is adequately at hand.

A great deal of practical experience has been collected on the dry grinding of coal for many purposes, including its use in coal-fired utility boilers. Therefore, in most demonstration plants the COM fuel has been prepared by grinding the coal dry and then dispersing it in oil to make the pumpable slurry fuel (9).

Dry grinding is a very efficient operation and easily implemented when one can blow the air used to sweep the grinding mills directly into the boiler with the fine coal dust. This is commonly done in utility boilers. However, when it is necessary to remove the air from the coal, cyclones as well as baghouses must be used to control the dust. This can cause an explosion hazard and an inert or oxygen-poor carrier gas is then required, causing a further complication. Furthermore, the dry-ground coal is usually slightly oxidized and not readily wetted by the oil. Therefore, also dispersion takes considerable effort before a well-stirred, homogeneous mixture of coal in oil is obtained. The result is a relatively complex, equipment-intensive system.

Many different kinds of mills may be used for dry grinding. These include ring roller mills, ball and race mills and cage mills. The first two require air sweeping and, hence, its subsequent disengagement; internal classification allows the standard fuel particle size to be obtained in one pass. The cage mill does not require use of air but typically two or three grinding stages are needed for a sufficiently fine grind. Blanketing of the mills with inert gas is required.

These problems can be avoided when the coal is ground wet, either in water for beneficiation or directly in oil for the simplest possible arrangement. The complex system described above is simply replaced by a single mill. However, there is limited availability of mills capable of grinding coal wet, particularly in viscous oil. The chief candidates are ball mills which have been used to grind coal in #6 oil down to the conventional boiler size of 75 or 80% passing 200 mesh (74 μm). There are various agitated media mills such as the Attritor which can also grind much finer if required, and the novel Szego mill which is still in the development phase but has proven itself effective for grinding coal in water or in oil.

Sato (10) has reported on extensive Japanese work in a ball mill 2.4 m long and 1.2 m in diameter containing 3.7 tons of balls. The objective was to grind to 75% minus 200 mesh, with a starting feed size of 80% - 3 mm. A production rate of 1000 kg/h of COM was attained, with the mill drawing 29 kW of power (or 23 kW exclusive of empty mill power). Grinding was carried out at 90°C. Good results were obtained at 50 and 55% coal in oil whereas grinding efficiency was significantly reduced at the 60% COM concentration. The energy required per ton of coal, in kWh, is roughly twice the aforementioned figures. A larger installation producing 10 t/h of COM is operating in Japan but no performance data are available.

The Attritor is an efficient mill in the relatively fine grinding range so that a pre-grinding stage is necessary. Typically, the mills are larger than ball mills for similar service and the power consumption is slightly higher. Some performance data for grinding in water are reported in (3). Singh (11) in a comparative evaluation of COM preparation techniques reports a specific energy consumption of 70 kWh/ton of coal for the Attritor along with twice the size of the Japanese ball mill required for the same rate of production. Other agitated media mills may be expected to have comparable operating rates and grinding efficiencies. The Tower mill has a lower power consumption than that of other agitated media mills, but its grinding rate is also appreciably lower, requiring an even larger mill volume.

The Szego mill is a new entry in this field and therefore warrants a brief description. It consists principally of a stationary, cylindrical grinding surface inside which a number of helically grooved rollers rotate, being suspended by flexible wire rope shafts from flanges connected to a central drive shaft. The feed material enters at the top and the product is discharged at the bottom of the mill. The particles, upon entering the grinding unit are repeatedly crushed between the rollers and the stationary grinding surface. The crushing force is created mainly by the radial acceleration of the rollers. An important feature is the ability of the roller grooves to aid transport of the material through the mill, thus providing a means to control residence time and mill capacity. The mill has been patented.

This mill has been used for grinding coal in both water and oil (12,13). It can handle pumpable slurries, work having been done at 42 weight percent of coal in #2, #4 and #6 oils (13) as well as pastes with a solids content of about 65% coal in oil (12). Indeed, while ultimate grinding performance is comparable, mill capacity in the paste grinding mode is significantly higher.

For the small, 22 cm diameter mills the feed should be -10 mm while in the larger units being tested a top size of 20 mm is readily handled. Product size distributions are comparable to those obtained in a ball mill, or slightly narrower. The 22 cm diameter mill, equipped with three 30 cm long rollers operating at 1200 RPM can grind 400 - 600 kg/h of coal at a 65% coal-in-oil consistency to 80% - 200 mesh. The specific energy consumption is 25 - 40 kWh/t of coal depending on oil viscosity. The mill can also be used in multi-pass operation to grind the product finer, quite readily down to the 15 μm median size (12).

The Szego mill is an order of magnitude smaller than other mills with which it could be compared, for the same capacity. The 22 cm diameter mill can readily produce one ton of COM per hour, equal to the production rate of the large ball mill reported earlier. It has been used to grind up to 1200 kg of coal/hour. While it is more complex mechanically, and due to its compactness more susceptible to wear,

it shows a distinct advantage over other equipment, particularly when space is at a premium.

Singh (11) has recently compared alternative technologies for preparing coal-oil mixtures to use as ignition fuel for Ontario Hydro's coal fired power stations. He compared Hydro's conventional dry grinding system, with air removal and coal dispersal in oil, the cage mill, and three wet grinding schemes, viz. the ball mill, the Attritor and the Szego mill. The comparison dealt basically with cost of installation and operation of these different systems and it was concluded that the Szego mill, in part due to its lower capital investment and total system simplicity offered the best prospect for efficient COM preparation.

Before leaving the conventional COM fuels, some comments should be made about the desirable coal particle size. Demonstration projects have used the conventional 80% - 200 mesh. Nevertheless, grinding to a finer size would bestow major advantages both from the point of view of combustion as well as slurry handling and, above all, stability. Cochran and Sell (14) have presented a convincing case for grinding coal significantly finer, to the "ultra-fine" size with a medium value of perhaps 15 μm. They argue that the benefits considerably outweigh the additional grinding costs (which are high in their proposed fluid energy mill system). The major compensating saving would be elimination of additives otherwise required to make the slurry stable, and the reduced erosion of lines and handling equipment, primarily pumps and valves and atomizing nozzles. With much finer particle one would also expect much improved combustion.

## Coal-Oil-Water Mixture Fuels

Extensive test work both in the USA (5) and Canada (6) has proven the value of these emulsified fuels. An ultrasonic treatment after grinding and mixing gives a very stable COW slurry. The need for any additives is eliminated. Pumping characteristics are apparently good and when this fuel burns, the water which is largely contained in or near the coal particles will flash in an explosive manner and shatter these particles into many tiny pieces. Therefore, ultrafine grinding is necessary neither for stability nor combustion reasons, the latter being taken care of by these micro-explosions.

The heat load is of course increased because the water must be evaporated, but the coal/oil ratio can be higher than in COM fuels. The recommended amount of water varies in the range of 12 to 20%; for thermal efficiency, low percentages are preferable.

Another useful step has been taken by Scotia Liquicoal Ltd. (6) in combining such COM fuel preparation with coal beneficiation. They grind their coal in water and then use the spherical agglomeration technique to beneficiate the coal into an oil phase. This process, developed at the NRC in Ottawa (13), relies on contacting the ash-laden coal-water mixture with finely dispersed oil droplets to which the hydrophobic coal particles adhere leaving the hydrophilic ash behind in water. The small coal agglomerates can then be screened off, with 99% coal recovery. The technique can remove about half of the ash and some pyrites, in part depending on how fine the grind is compared to ash liberation size. The product contains a certain amount of water and may only need to be blended with additional oil to get a suitable COW fuel mixture which is then passed through the ultrasonic device to emulsify and stabilize it for future combustion. This process allows use of higher ash content coals and/or reduces the heating value penalty caused by ash in the COM.

## Coal-Oil-Methanol Fuels

It has been proposed as another alternative to add small amounts of methanol to coal before dispersal in oil for COM preparation. As described by Keller (7) such fuels would have good stability, desirable rheology, much enhanced ignition and good combustion with the mini-explosions but without fuel penalty; instead, the alcohol adds to the fuel value of the mixture.

Some testing of such fuels has apparently been done but no additional information is available at this time. With the potential of cheap fuel grade methanol from large plants, this may be an attractive proposition.

## Coal-Water Slurry Fuels

As the price of oil has escalated much beyond early expectations, interest has intensified on possible approaches where a pumpable coal-containing fuel may be prepared without the use of any oil. At the Third International Symposium on Coal-Oil Mixture Combustion, in Orlando, Florida, April 1981, there was considerable interest in coal-water (CWM) fuels. The Swedish "carbogel" has been tested and may be approaching commercial production in a country where all of the oil has to be imported, but little has been published about it. Atlantic Research Corp. (18) among others has also reported on a similar development in the U.S.A. Test firings have been carried out and major further developments in coal-water fuel technology in the next few years are certain. These may make the COM fuels even more a short-term interim solution only.

Grinding alternatives for CWM fuel preparation are similar to those discussed earlier; one can grind dry and then disperse, or one can grind wet directly. Again, wet grinding has the advantage of simpler equipment and fewer concerns.

It is obviously desirable to make the coal concentration as high as possible to reduce the economic penalty of having to evaporate all that water. Apparently, a solids concentration of 70% can be used, with additives to reduce viscosity. Settling in such highly loaded slurries should be minor but must be prevented by yet other additives to avoid formation of a hard, solid deposit. Assisted ignition is required but it appears that the CWM fuel can thereafter burn quite stably. The importance of particle size has not yet been publicly described. The U.S. effort (8) appears to be along conventional lines; the "carbogel" fuel is reputed to be much finer.

## Coal Beneficiation

Compared to oil, any COM will contain significantly more ash. Depending on the sulfur content of the coal and of the oil it replaces this may or may not be an additional problem. In both cases beneficiation of the coal would seem attractive. All the conventional beneficiation schemes may be utilized, such as heavy media separation, or flotation for smaller coal particle sizes. If the coal is to be used subsequently in a COM fuel, the NRC spherical agglomeration technique will have a major advantage as described earlier.

Water content of the agglomerates can be controlled and spherical agglomeration may be used to dry coal or other materials without recourse to thermal means (15). It is possible to use a light hydrocarbon solvent rather than oil in the agglomeration step. One can then recover the solvent and be left with a clean, dry coal which may be used as a powdered fuel, or to prepare a coal-water slurry. For the latter application the particular advantage of the spherical agglomeration technique is lost and a decision between this approach or conventional flotation will be a matter of economics.

## Combustion Characteristics

Much of the initial utility boiler test work with COM fuels has been carried out in boilers which were originally designed for coal firing and had been converted to heavy oil during the 1950's. Therefore, tube spacings were large and the residence time in the combustion section long enough to allow essentially complete combustion of the COM with the conventional coal particle size. When the same mixtures are fired in boilers designed originally for oil, matters become more complicated since a dual flame front will exist: initially much of the oil will burn off and there will be a second, extended flame region where the coal particles burn. The larger particles may, therefore, not have time to burn completely. The extent of this concern obviously depends on the fraction of coarse coal particles, and grinding to a

smaller mean size as proposed by Cochran and Sell (14) would obviously help a great deal. The mini-explosions resulting from small amounts of water or methanol associated with coal in the fuel have the same beneficial effect.

No serious study of flame characteristics and their dependence on coal-oil ratio, coal particle size, or possible water level has been undertaken. A considerable amount of work is going on in various laboratories and important results may be expected in the near future. For COM fuel preparation, aside from particle size objectives, this is not as much of a concern as it is to those who must convert oil fired boilers to COM usage.

Due to the presence of a certain amount of ash it will be necessary to install soot blowers to boilers which do not already have these. Smaller particles will apparently not reduce ash deposition; they will, however, give a slight improvement in both carbon conversion and boiler efficiency (16). The concerns about derating of boiler capacity with COM fuels as against #6 oil appear to have been overly pessimistic. No derating has been observed by Pan et al (17) in a 700 HP watertube boiler designed for oil firing, and this is not an isolated case.

## Slurry Properties

A great deal of work has been done on both rheology and stability of COM fuels. Several sessions were devoted to these topics at all three International Symposia on COM Combustion. Unfortunately, there appear to be as many problems and questions to be answered as there are different kinds of coals and oils and their combinations. A stabilizing additive, for example, which does wonders in case A may fail dismally in case B, so generalization is difficult. Ekmann and Bienstock (18) and others have discussed this topic.

Settling characteristics are important not only for COM fuel storage, particularly with central preparation facilities, but also for subsequent handling. Should, for example, flow in a transport line stop for an extended period, flow of a settling slurry could not be started up again without cleaning out the compact sediment at the bottom. Requirements vary widely and depend on design and operating conditions of the individual installations.

There are significant deviations between various reported COM rheology data, usually obtained as a part of other major work. Papachristodoulou and Trass (19) have recently reported on the rheological properties of ultrafine COM fuels prepared with the Szego mill covering wide ranges of temperature and composition, with Pittsburgh coal and #2, #4 and #6 oils. Work is continuing with different, larger particle size slurries. Typically the data are in good agreement with those published by Munro et al (20). Both studies show that the slurries are Newtonian over wide shear rate ranges at low concentrations and start to exhibit Bingham plastic behaviour at or above 30% coal in oil, with the observed yield stress increasing with coal concentration, but still with a linear stress-strain relationship.

Such data are important both for the transportation of COM fuels whether this be in short pipelines or in transfer lines between pieces of equipment, and also to predict behaviour in the much higher shear rate atomizing nozzle flows for furnace injection.

## COM Fuel Preparation Strategies

Some remaining points should be addressed, at least briefly. These deal with obtaining the COM fuel from a central preparation plant, or setting up a local dedicated facility, with storage, or for on-line operation. It is possible for a large user, particularly when he has his own coal handling facilities, to set up his COM preparation plant on site, space permitting. He may wish to provide for some storage capacity so that there is a large supply, or at least one day's supply available, to be pumped through transfer lines to the boilers.

Alternatively, the user may consider an on-line system with only minimal storage facilities. In the latter case, if there is sufficient space available at the boiler

site, it may be possible to set up the facility close to the boiler, thus reducing the cost of transfer lines. A study by the Tennessee Valley Authority (21) has shown that the major cost of a COM installation, in their case for boiler light-off fuel, is associated with piping and storage rather than with actual COM preparation.

If a potential user does not have his own coal handling facilities he may consider building these and storing his own coal for on-site preparation of COM fuel, space permitting. Alternatively, he may consider purchasing the COM fuel from a central preparation facility which should serve a small industrial area, piping the fuel to nearby and larger customers and transporting it by truck or rail to others. Holbrook and Schelat (22) have discussed the prospects of such regional COM preparation facilities. Whenever space is at a premium or usage is not large, reliance on a central facility is favoured.

With such central COM preparation facilities, slurry stability is of paramount importance, whereas with on-line preparation systems it is much less significant -- other handling and combustion characteristics would take precedence in determining desirable slurry properties.

Early plans relied on dry grinding and dispersal of coal. For this equipment-intensive operation, large central facilities were favoured so that economics of scale of COM preparation could benefit both the supplier and the user. With wet grinding as the preferred mode, smaller installations, both for regional and on-site use, can also be economical due to their inherent simplicity. In a comparative paper of COM fuel costs, O'Neill et al (23) concluded that the major cost is always the coal and the oil, and different preparation techniques have only a minor influence. While this is true, the important differential between total cost and raw materials cost is strongly influenced by the preparation technology and the equipment chosen.

The idea of continuous, on-line COM preparation, while attractive in saving storage tank and piping costs, suffers from the fact that in many situations there is not much space available near the boiler to accommodate the grinding equipment. With large, low capacity equipment such as the Tower mill or the Attritor, this may not be possible, where as with the small, high capacity Szego mill such an installation could be accommodated even in very confined circumstances. Space requirements of the mill are minimal.

It appeared at the Orlando Symposium that the many potential COM users were hesitant to go ahead and convert without assured supplies of COM fuels, and potential fuel manufacturers hesitated in making the investments required to prepare such fuels without a firm sales commitment. As a result, while adequate technology is available both for COM preparation and for the users' needs, and conversion could be very rapid, bunker oil is still being burned in most boilers. Nevertheless, at least a few companies in the USA (5,22,24) and one in Canada (6) are going ahead with plans to prepare COM fuels. Some of these are joint activities with users so that there is an assured, initial base market available. Once that barrier of hesitation is broken, rapid introduction of coal slurry fuels may be anticipated in both utility and industrial boilers.

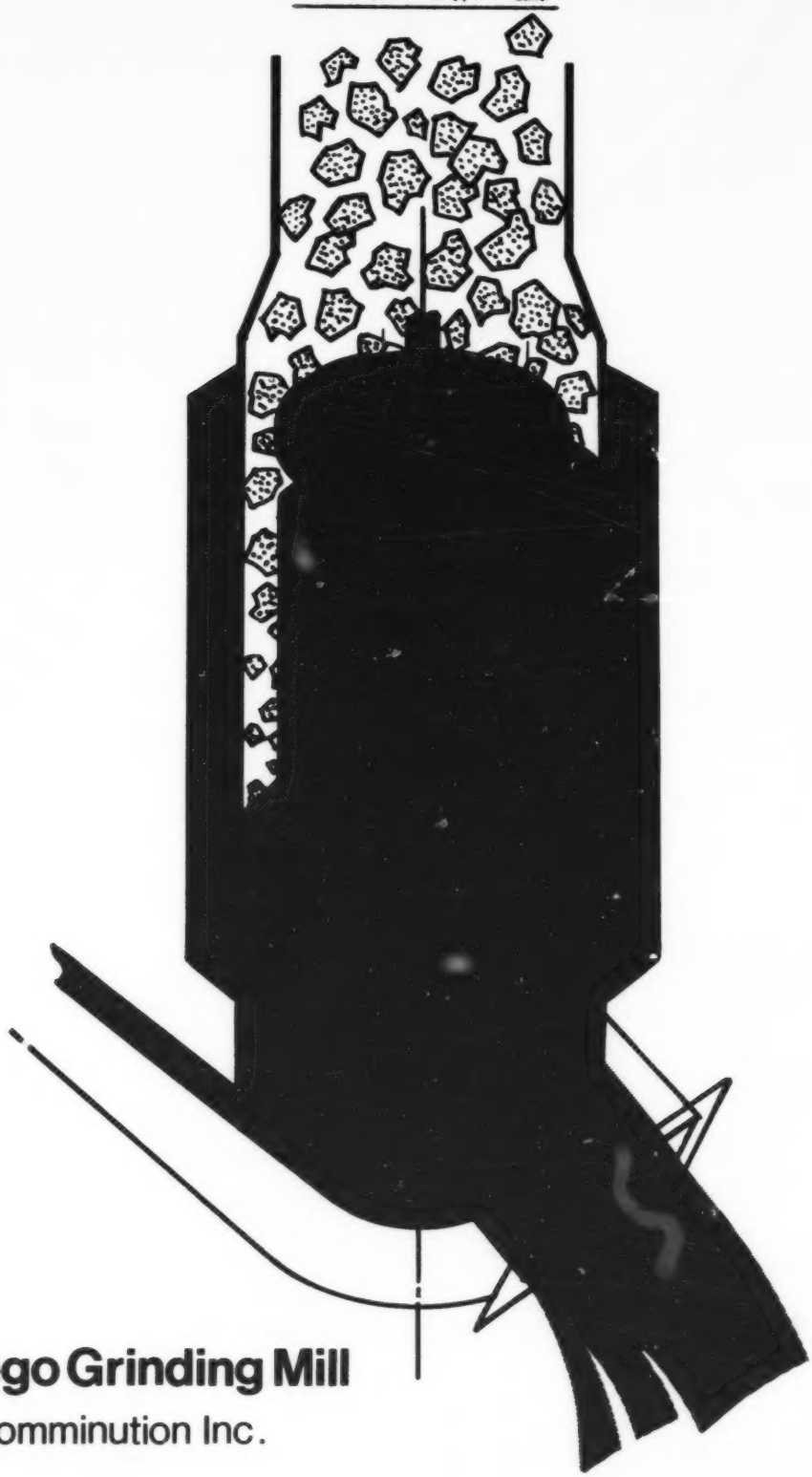
The next challenge, one which could also extend the useful life of COM fuels technology, is that of adapting these fuels for use in diesel engines. The requirements are much more exacting, but the rewards can be correspondingly higher.

## References


1. Kuehnel, R., "COM Profitability: Sensitivity to Coal-Oil Price Differentials", Proc. 1st Intl. Symp. on Coal-Oil Mixture Combustion, Blake, J.C. and Sabadell, A.J., Eds., The MITRE Corporation, McLean, VA, p. 347 (1978).
2. Whalen, P.J., Davies, F.W., Lee, L.K. and Mitchell, K.A., "A Study of Coal Agglomeration and Coal-Oil Mixture Combustion in a Utility Boiler", Final Report to EMR, DSS Contract 18 Sq.23440-7-9055, Fredericton, N.B. (1979).

3. Canadian Combustion Research Laboratory, "Proceedings of the Coal-in-Oil Seminar, May 1972", Fuels Res. Centre Divisional Rept. FRC 72/95, CCRL (1972).
4. Leffert, C.B. and Piccirelli, R.A., "First Report of the General Motors Corp. Powdered Coal-in-Oil Mixture Program", EPRI Contract No. RP527, Dec. 1976.
5. Hawkins, G.T., "Commercial COM Operation, An Up-date", 3rd Intl. Symp. on COM Combustion, Orlando, FL, April 1981.
6. Poetschke, L., "Liquicoal Demonstration Project", ibid.
7. Keller, L.J., "The CFOS Fuels: Carbonaceous Fuel-in-Oil Suspensoids", 2nd Intl. Symp. on COM Combustion, Danvers, MA, November 1979.
8. Sheffee, R.S., Rossmeissl, N.P., Boyd, T.J., Henderson, C.B. and McHale, E.T., "Development and Burning of Coal/Water Slurries", 3rd Intl. Symp. on COM Combustio, Orlando, FL, April 1981.
9. Slepow, L.D. and Mendelssohn, A.S., "FPL's Sanford COM Demonstration Project", ibid.
10. Sato, N., "Results of Experimental Production of Fine COM by Wet Type Mill", 2nd Intl. Symp. on COM Combustion, Danvers, MA, November 1979.
11. Singh, V.P., "Boiler Ignition with Coal/#2 Oil Mixtures", Rept. No. 81-91-K Research Div. Ontario Hydro, Toronto, Ontario (1981).
12. Trass, O., Papachristodoulou, G., Gandolfi, E.A.J. and Rouse, J.D., "Grinding of Coal Slurries with the Szego Mill", Symp. Coal: Phoenix of the 80's, C.I.C. Ann. Mtg., Halifax, N.S., June 1981.
13. Trass, O. and Papachristodoulou, G., "Grinding of Coal-in-Oil Slurries with the Szego Mill", 2nd Intl. Symp. on COM Combustion, Danvers, MA, November 1979.
14. Cochran, J.W. and Sell, F.R., "Progress in Developing Ultrafine Coal-Oil Mixtures", ibid.
15. Capes, C.E., "Principles and Applications of Size Enlargement in Liquid Systems", Fine Particles Processing, P. Somasundaran, Ed., Vol. 2, 1442, AIME, N.Y. (1980).
16. Pan, Y.S., Wildman, D.J., Bellas, G.T., Joubert, J.I., "Effect of Coal Particle Size Consist on the Performance of a COM-Fired Boiler", 2nd Intl. Symp. on COM Combustion, Orlando, FL, April 1981.
17. Pan, Y.S., Bellas, G.T., Mathur, M.P. and Bienstock, D., "Combustion of Coal-Oil Mixtures in a 700 HP Watertube Boiler", 2nd Intl. Symp. on COM Combustion, Danvers, MA, November 1979.
18. Ekmann, J.M. and Bienstock, D., "The Role of Coal and Oil Characteristics in the Stability of Coal-Oil Mixtures", ibid.
19. Papachristodoulou, G. and Trass, O., "Rheological Properties of Ultrafine Coal-Oil Mixtures", 3rd Intl. Symp. on COM Combustion, Orlando, FL, April 1981.
20. Munro, J.M., Lewellyn, M.M., Cracker, P.R. and Bauer, L.G., "A Characterization of Rheological Properties of Coal-Fuel Oil Slurries", AIChE Jour., 25, 355 (1979).
21. Smith, R.R., Cole, R.M., Cox, R.B., Derbige, T.C., Schreiber, R.J. and Yasuda, A.K., "Investigation of Coal-Oil Mixtures as a Utility Boiler Light-Off Fuel", 2nd Intl. Symp. on COM Combustion, Danvers, MA, November 1979.
22. Holbrook, W.D. and Shelat, T.A., "A Scenario for Regional COM Preparation", 3nd Intl. Symp. on COM Combustion, Orlando, FL, April 1981.
23. O'Neill, J.K., Kinnenberg, D.J. and Viola, M.A., "A Comparative Study of COM Preparation Technologies", ibid.
24. Knell, E.W., and Bauer, H.P., "Status of the Occidental Coal-Oil Mixture Program", ibid.

APPENDIX III



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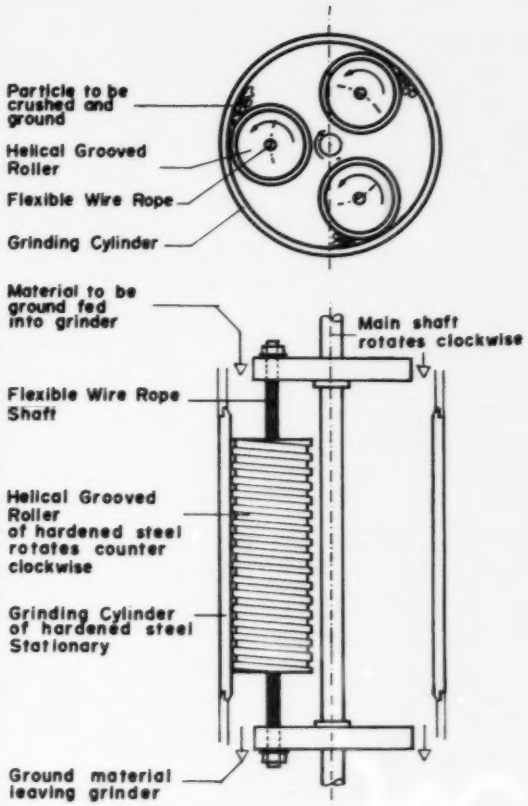
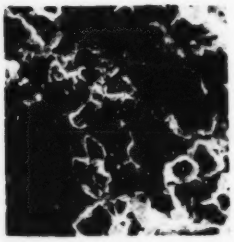

Particle to be crushed and ground
Helical Grooved Roller
Flexible Wire Rope
Grinding Cylinder
Material to be ground fed into grinder
Main shaft rotates clockwise
Flexible Wire Rope Shaft
Helical Grooved Roller of hardened steel rotates counter clockwise
Grinding Cylinder of hardened steel Stationary
Ground material leaving grinder

Schematic diagram of the Szego Mill.

## ELECTRON MICROGRAPHS OF SOME PRODUCTS



— ALUMINUM

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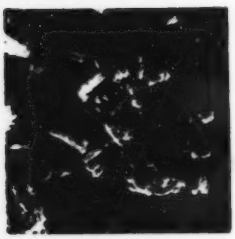

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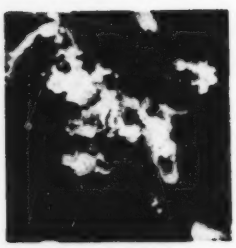

— COAL

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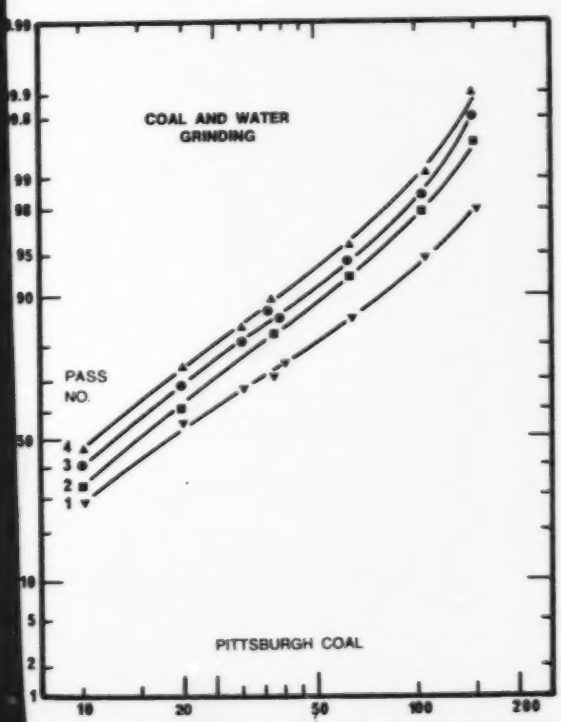


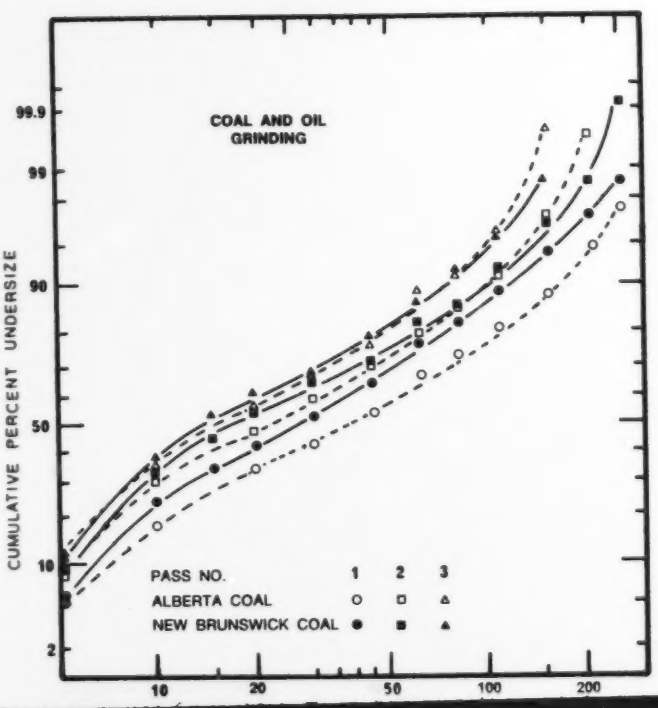

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